ICT-248891 STP FREEDOM

Femtocell-based network enhancement by interference management and coordination of information for seamless connectivity

D4.2

Design and evaluation of effective procedures for MAC layer

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Abstract:

The implementation of femtocells introduces many technical challenges that must be solved in order to fully exploit their potentials. This deliverable primarily focuses on control procedures for radio resource management addressing the most critical issues. To utilize radio resources of femtocell efficiently, a novel routing of data among users served by the same femtocell is proposed. Furthermore, spectrum-efficient technique for power control, scheduling (both at radio side and backhaul side and multicast/broadcast services transmissions are designed. Additionally, novel authorization approaches and femtocells' identification technique are proposed while taking in consideration the scalability of the system. Besides the optimization of radio resource management procedures, this document designs and specifies the control plane procedures to ensure effective coordination among femtocells and macrocell designed in WP3. Finally, cross-layer optimization issues are addressed here by means of optimal femtocells' power allocation derivation using the Game Theory framework.

Keyword list: authorization, control procedures, cooperation, cross-layer optimization, emergency call, multicast and broadcast services, power control, routing, scheduling.

Document Revision History

DATE	ISSUE	AUTHOR	SUMMARY OF MAIN CHANGES
2010-06-30	a	P. Mach	Initial table of content and proposed structure
2010-11-05	b	All partners	Compilation of all contributions from all partners
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Executive Summary

This deliverable summarizes the research activities carried out in 4A2 task in frame of WP4. The main focus is on radio resource management in networks exploiting femtocells. The objective is to propose control procedures to address key problems relating to femtocells' implementation. The first three sections (**Sections 1-3**) give an overview on the state of the art, general assumptions and scenarios, with respect to D2.1 document, considered further in the technical part of the document.

The proposal of individual control procedure is addressed in **Section 4**, which focuses on several research topics. The first topic, described in **Section 4.1**, deals with efficient **routing procedure** when **two users connected to the same Femto Access Point (FAP) communicate with each other**. We propose novel routing scheme managing data transmission directly instead of two hop communication. This way, the radio resources allocated to the femtocells are more efficiently utilized. Whether direct transmission is feasible or not is evaluated at the femtocell using Radio Resource Cost metric. In addition, we propose management procedure in order to implement our routing scheme into LTE-A standard. It is demonstrated that our proposal outperforms conventional routing approach both in terms of throughput and packet delays experienced by users in uplink. The performance of the proposal is less degraded for higher PER than the performance of the conventional scheme. Regarding the overhead generated by our proposal, although the worst case situation is considered, still additional overhead is negligible.

The next topic, addressed in **Section 4.2**, is focused on **fast power control procedure**. The basic idea is to **adapt the transmitting power of femtocells according to current traffic load** and signal quality between user equipments and the femtocell in order to **fully utilize radio resources allocated to the FAP**. The advantage of the proposed scheme is in provisioning of high quality of service level to the femtocell users while interference to users attached to macro base station is minimized. The proposal performance is evaluated in terms of mobility events (handovers), achieved throughput, and femtocells transmitting power and results are compared to existing power algorithms. The results demonstrate that the proposed mechanism significantly outperforms schemes trying to cover the whole coverage. Still, the proposal is able to guarantee the same Quality of Service to femtocell's users as those approaches. If proposed scheme is compared to scheme trying to minimize the amount of mobility events at the cost of femtocell' users, our proposal is always better as long as the generated traffic is at light or medium levels and sufficient amount of radio resources is allocated to the femtocell. Nonetheless, with optimized power adaptation step equal to 2 dB, the proposal outperforms this scheme also at heavy traffic load if sufficient amount of radio resources is allocated to the femtocell while it still enables the coverage of all users in the house.

Other topic related to the potential advanced service for femtocell is the implementation of **Multimedia Broadcast and Multicast Services (MBMS)** in femtocell network addressed in **Section 4.3**. The MBMS as defined by 3GPP is the technique to efficiently deliver Multimedia service in either broadcast or multicast mode through wireless networks. Similarly as LTE has developed into LTE-A, MBMS also has evolved to e-MBMS. This technique introduces new transmission mode known as Single Frequency Network (SFN) besides existing Point to Point (PtP) and Point to Multipoint (PtM) mode. The idea to introduce MBMS in femtocell is driven by the fact that multimedia services can be more enjoyable to consume inside a premises which are also the target place to implement femtocell networks. This leads to an idea of combining those two technologies in order to have all of their benefits in delivering new services in femtocell networks. The simulation results show the better performance of multimedia service delivery in femtocell area using femtocell based MBMS compared to non-femtocell MBMS. Other results also show the promising SFN mode as the best performance mode compared to other transmission modes. This early research will clear the way for more advanced study in investigating other aspects as well as deep assessment needed for implementing MBMS in femtocell networks.

Section 4.4 deals with problem relating to **assignment of physical cell identities (PCIs) in the femtocell environment**. Based on study of femtocell density per macrocell when considering different macrocells/femtocell radii and available PCIs, we propose a novel structuring of PCI. The basic idea is to enhance the PCI structure about a new identifier called FAP cluster identifier where a FAP cluster is comprised of set of neighboring FAPs. The FAP cluster identifier can be specified either as extension or as sub-identifier of current PCI structure. The proposed structure makes possible to adjust in time from macrocell to macrocell the range of used PCIs.

The authorization of a user who is accessing a closed femtocell at which the user is not included in closed subscriber group (CSG) list is delivered in **Section 4.5**. The two situations of such authorization are investigated. First, the authorization procedure of so-called visiting users to CSG FAPs is proposed. Conventionally, the user, which is not included in the CSG list, cannot access the CSG FAP. We propose a control procedure to enable temporary access of the visiting user to the CSG FAP if this access is approved by a FAP subscriber. Two options of management communication are designed: in-band and out-of-band. The first one is completely performed via the radio access technology (e.g., LTE or LTE-A) while the second one requires additional technology (e.g., Bluetooth). For the second option, out-of-band communication technology must be enabled on visiting UE equipment and the UE of the FAP subscriber. On the other hand, it introduces no additional overhead on communication channels. Second, the procedure of **an access of users in case of an emergency call** is proposed. We propose a control procedure to enable access of the user to the CSG FAP. The control procedure includes already defined messages by 3GPP, however in specific order. In addition, management of the network shall allow this access in the case of emergency call.

Section 4.6 specifies the **control plane procedures** to operate in FREEDOM environment and making practical the coordination schemes designed in WP3. To enable the exchange of control information between the different FAPs (or MBS and FAPs), new information elements are designed. In the proposed messages, a limited number of bits is employed to encode the parameters to be exchanged. The performance **degradation due to quantization** with a limit number of bits compared to the ideal case of having infinite bits available is evaluated. From the number of bits required to exchange the control information, an estimation of the **overhead due to the control information exchange** is done for the FREEDOM scenario.

Scheduling techniques are addressed in **Section 5**. **Section 5.1** focuses on **advanced scheduling techniques** with the aim to mitigate femto to macro interferences in the downlink, without reducing the efficiency of opportunistic scheduling. In order to implement them into standard, the modification are specified and their benefits are demonstrated by means of evaluation. **Section 5.2** introduces **new scheduling method called Backhaul Aware Scheduling (BAS)**. This study was driven by the limitation of backhaul capacity (e.g., bottleneck or congestion) caused by other traffic (e.g., IPTV or Internet access) which affects the performance of FAP in serving requested traffic from femtocell users. The admission control is incorporated with the scheduling method to treat all kind of traffic served by FAP. With BAS, the FAP can decide whether the backhaul capacity is enough to support existing session. The simulation results show that with BAS, the performance of FAP can be improved especially for peak backhaul conditions compared to FAP without BAS.

Section 6 addresses the problem of **optimal scheduling in OFDMA femtocell networks**. In such networks, different subcarriers can be allocated to different users to provide a flexible multiuser access scheme and to exploit multiuser diversity. Hence providing efficient resource allocation among the users in the system becomes a fundamental problem. On one hand, the scheduling algorithm has to prioritize the requests according to the user quality-of-service (QoS) requirements. On the other hand, the wireless channels offer *physical layer resources* lying in the frequency and time domain. So, the conventional isolated design approach of optimizing the physical layer and the MAC layer separately fails to exploit the dynamic nature of the physical layer and is suboptimal in multiuser wireless channels. This motivates *cross-layer approaches* where the MAC layer and the physical layer are jointly optimized.

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List of abbreviations & symbols

ACA	Adaptive Coverage Adjustment
ACK	positive ACKnowledgement
ACS-MB	Auto-Configuration Scheme-Mobility Based
AMC	Adaptive Modulation and Coding
ANR	Automatic Neighbour Relation
ATI	Allocation Time Interval
AWGN	Additive White Gaussian Noise
BE	Best Effort
BAS	Backhaul Aware Scheduling
BSR	Buffer Status Report
CAC	Connection Admission Control
CBR	Constant Bit Rate
CDF	Cumulative Density Function
CID	Connection Identifier
CINR	Carrier to Noise and Interference Ratio
CLC	CSG List Control
CMAS	Commercial Mobile Alert System
CoMP	Coordinated Multi Point
CP	Cyclic Prefix
CPC	Conventional Power Control
CQI	Channel Quality Indicator
CSG	Close Subscriber Group
CSI	Channel state information
CVQ	Channel Vector Quantization
DL	Downlink
DLICI	DL interference cost indication
DL-SCH	Downlink Shared Chanel
e-BM-SC	evolved Broadcast Multicast Service Centre
EDF	Earliest Deadline First
ECGI	E-UTRAN cell global identifier
e-MBMS GW	e-MBMS Gateway
e-NodeB	evolved NodeBs
EPC	Evolved Packet Core
ertPS	Extended real time Polling Service
e-UTRAN	evolved UMTS Terrestrial Radio Access Network
ETWS	Earthquake and Tsunami Warning service
FAP	Femto Access Point
FUE	Femto User Equipment
FDD	Frequency Division Duplex
FPBX	Femto Private Branch Exchange
HARQ	Hybrid Automatic Repeat request
HeNB	Home eNodeB
HeNB-GW	Home eNodeB GateWay
HII	High-interference Indicator
GT	Game Theory
GTP	GPRS Tunneling Protocol
GW	Gateway
IE	Information Element
ID	Identificator
IP	Internet Protocol
IMS	IP Multimedia Subsystem
LMA	Local Mobility Anchor

LTE	Long Term Evolution
MAG	Mobile Access Gateway
MBS	Macro Base Station
MCCH	Multicast Control Channel
MCH	Multicast Channel
MCE	Multi-cell/multicast Coordination Entity
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MME	Mobility Management Entity
MT	Mobile Termination
MTCH	Multicast Traffic Channel
NACK	Negative ACKnowledgement
NAS	Non-Access Stratum
NE	Nash Equilibrium
nrtPS	Non real time Polling Service
OI	Overload Indicator
OSG	Open Subscriber Group
PCFICH	Physical Control Format Indicator Channel
PDCCH	Physical Downlink Control Channel
PDN	Packet Data Networks
PHICH	Physical Hybrid ARQ Indicator Channel
PCI	Physical Cell Identity
PDN-GW	Packet Data Network Gateway
PMI	Precoding matrix indicator
PMIPv6	Proxy Mobile IP v6
PPC	Proposed Power Control
PRACH	Physical Random Access Channel
PRB	Physical resource block
PtM	Point-to-Multipoint
PtP	Point-to-Point
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
PS	Proposed Scheme
PSS	Primary Synchronization Signal
RAP	Random Access Procedure
RI	Rank indication
RNTP	Relative Narrowband Transmission Power
rtPS	Real-time Polling Service
RRC	Radio Resource Control
RS	Reference Signal
S-GW	Serving GateWay
SE	Spectral Efficiency
SFN	Single Frequency Network
SINR	Signal-to-Interference plus Noise Ratio
SIP	Session Initiation Protocol
SISO	Single Input Single Output
SOS	Self Optimization Scheme
SR	Scheduling Request
SSS	Secondary Synchronization Signal
TA	Terminal Adaptor
TDD	Time Division Duplex
TE	Terminal Equipment
TOF	Traffic Offload Function

TTI	Transmit Time Interval
UE	User Equipment
UGS	Unsolicited Grant Service
USIM	Universal Subscriber Identity Module
V-UE	Visiting UE
WFQ	Weighted Fair Queuing
W^2FQ	Worst-case Weighted Fair Queuing
X2AP	X2 Application Protocol

1 INTRODUCTION

The implementation of femtocells, represented by femto access points (FAPs), can significantly improve network performance. Nevertheless, several key issues have to be addressed to fully exploit their potentials. To that end, the main objective of this deliverable is to propose new techniques and control procedures for wireless networks implementing FAPs. All the objectives mainly contemplate the techniques specified for LTE/LTE-A with closed access, but also open/hybrid access and other technology platform (i.e., WiMAX), are taken into consideration for specific investigation.

One important research topic is to guarantee efficient packet routing. New ways for routing of data packets can be found in dense deployment of FAPs. Besides conventional scenario, when user's data are routed through backbone to the destination, the scenario for direct communication excluding backbone raises (e.g., when both communicating user's are connected to the same FAP or to the different FAPs owned by the same user). It enables the design of new paradigms to route traffic within one femtocell or among femtocells for better utilization of limited backbone capacity.

Other aspect that needs to be addressed is how to avoid the harmful interference either to a macro BS (MBS) or to neighbor FAPs if the same spectrum is utilized by the MBS and FAPs. The effective way for interference avoidance is an appropriate power control mechanism. The power control mechanism may be implemented either in uplink or/and in downlink direction. In the former case, a transmission power of User Equipment (UE) is adapted. In the latter case, an adaptation of FAP's transmission power is accomplished. The targeted solution is to modify transmitting power of FAPs to dynamically adjust its transmitting power in order to decrease interference to outdoor users connected to the MBS.

To support potentially added services in Femtocell deployment, the delivery of multimedia real time services (broadcast/multicast) in Femtocell network gains much interest to investigate. The target is to evaluate the performance of possible transmission bearer techniques in MBMS (Multimedia Broadcast Multicast Services) to support the initiation and termination of session/transmission of multimedia traffic between UE and FAP in designated Femtocell MBMS service area.

The other problem introduced by FAP is related to limited number of available cell ids (Physical Cell Identity, PCI) since mobile networks are not ready to cope with implementation of ten (or hundreds) thousands of FAPs in the nowadays networks. The goal is to analyze femtocell density per macrocell when considering different macrocell/femtocell radii and available PCIs and based on this study to propose a new flexible concept of the cell identification that takes into account the large amount of femtocells.

Regarding authorization procedure, new ways have to be designed to allow connect non CSG users to FAP with closed access. Consequently, novel scenario of visiting user is designed and analyzed. Furthermore, the authorization of user accessing closed femtocell in case of emergency that user is not included in CSG of FAP. This is key issue especially if the FAP is the only available one in the user's vicinity.

An efficient and proactive way to cope with the harmful interference is designing precoders that avoid allocating too much power in the directions of those neighbors whose performance would be more compromised. This design requires some coordination among the different transmitters. More specifically, it requires the exchange of interference costs that measures the performance degradation due to a transmission from a neighbour station at each PRB. When the precoders are predefined, and the power and modulation and coding scheme (MCS) must be the same for all the PRBs allocated to a given user as it happens in LTE-A, a way to cope with interference is to select both the operational bandwidth part and beamformer in a coordinated manner among the set of close transmitters. This coordination requires the exchange of interference costs as well. In both cases, additional procedures and information elements to enable the computation and exchange of interference costs are required.

The degradation due to the exchange of a quantized version of such interference costs needs to be evaluated as well.

Another way to cope with interference issue between macro and femto tiers is to forbid the femtocell specific frequency bands. When macrocell to femtocell time synchronization is granted, static partitioning of OFDM resources between macro and femto tiers can be proposed for addressing this issue. As an example, a pool of OFDM resources may be forbidden to femtocells, and macro cell may exploit this pool whenever a macro user suffers from downlink femtocell interference. However such solutions bring strong scheduling constraints so that the efficiency of opportunistic scheduling becomes a concern. More advanced techniques (still based on this principle) are needed in order to address the interference issue without jeopardizing opportunistic scheduling benefits. Timer based interference mitigation is described in this document with such objective in mind.

The inherent problem of FAPs rests in their backhaul limitation ensured mostly by xDSL link. The backhaul conditions can affect the performance of FAP and thus its users as well. The capacity of femtocell backhaul is consumed not only by FAP but also by other devices and applications utilized by the broadband subscriber. Therefore the FAP needs to be aware of the condition of backhaul in order to maintain its performance. This leads to a backhaul aware scheduling method which introduces several techniques implemented in the FAP to effectively treat the incoming traffic based on the condition of the backhaul.

Since the physical and MAC layer issues cannot be handled separately, cross-layer optimization techniques need to be introduced. The problem of the optimal resources allocation in the downlink channel of an OFDMA femtocell network where FAPs share the same frequencies to transmit to their own users is considered. The optimal resource allocation problem consists in finding the optimum power allocation for each FAP to maximize the sum of the information rates of all the FUEs in each cell weighted by their queues length, subject to global power and peak power constraints, and treating the interference among FAPs as additive noise. Because of this interference the scheduling strategies of the FAPs are not independent a distributed solution with no centralized control among the interfering FAPs is proposed. Due to the inherently competitive nature of this multi-cell system we formulate the system design within the convenient framework of Game Theory (GT). GT framework is a helpful tool to devise distributed schemes able to converge to a steady-state solution, the celebrated Nash Equilibrium (NE).

2 STATE OF THE ART

This section describes related work of individual topics addressed in this deliverable in order to distinguish its progress beyond the state of the art.

2.1 Packet routing procedure

The important aspect regarding femtocells is to manage efficient routing of user's data. The objective is to select the most appropriate path to offload operator's core network and to offload limited FAP's backbone typically exploiting xDSL.

There are several studies on how to offload operator's core network. In [Roh11], the authors aim to offload core network from femtocell traffic by means of a Traffic Offload Function (TOF) entity. The TOF is located between femtocell gateway and core network and monitors whether data traffic is bound for operator network or for Internet. In the former case, the TOF allows to route data traffic in the direction of operator network. In the latter case, data traffic is directly sent to the Internet. Similarly, other paper proposes to offload core network and to minimize redundant data transmission through local breakout methods [Chiba10]. The authors consider that operator's network is based on IP Multimedia Subsystem (IMS) and thus all signaling is handled via SIP (Session Initiation Protocol). The authors propose an exchange of SIP messages to enable routing of data traffic through shorter paths not involving core network.

If data are transmitted between two stations located within the same company, campus, etc., there is effort to route data traffic via shorter path to offload FAP's backbone. In [Ling10], the authors propose Femto Private Branch Exchange (FPBX) to concentrate traffic of several FAPs in specific areas such as an enterprise or a campus. The advantage of FPBX is that the calls within the enterprise are routed in similar way as in the case of conventional PBX. Thus, the cost of the call is reduced. Another route optimization of data for femtocells is proposed in [Chiba09]. The authors suggest to route data directly between two FAPs that are in close vicinity of each other and thus to considerably offload FAP's backbone.

2.2 Power control

The power control mechanism may be implemented either in an uplink or in a downlink direction. In the former case, a transmission power of User Equipment (UE) is adapted. In the latter case, an adaptation of FAP's transmission power is accomplished. The power control in uplink is addressed, e.g., in [Jo09a][Chandrasekhar09a][Chandrasekhar09b]. Regarding the power control in downlink several mechanisms have been already proposed. Generally, two different approaches are followed regarding the downlink power control in femtocell's environments. According to the first approach, the main aim is to completely cover a specific area of certain radius (e.g., to ensure the whole household coverage). The advantage is that users are always able to connect to the FAP when inside the building. Nevertheless, the signal leakage out of the building boundaries may be significant. The primary goal of the second approach is to set the transmitting power of FAP to minimize interference to passerby's users or neighbouring FAPs. The disadvantage of this approach is that the coverage of whole building is not always assured, especially if the FAP is positioned close to the building boundary.

In [Claussen08][Claussen09], authors suggest auto-configuration schemes (representatives of the first approach) and self-optimization schemes (representatives of the second approach). While the auto-configuration schemes provide an initial power setting of the FAP, the self-optimization schemes try to optimize the FAP's transmitting power during a normal operation. Authors distinguish three auto-configuration schemes; i) fixed power, ii) distance based, and iii) measurement based. When fixed power configuration scheme is utilized, the transmitting power is set to fixed value (authors consider -

10 dBm). Disadvantage of this method is that the FAP's coverage strongly depends on the distance from the MBS. This drawback is eliminated by the distance or measurement based approaches. In these cases, the FAP power is configured so that the received signal from the strongest macro cell and the FAP is the same at a defined target cell radius. Usually the target cell radius corresponds to the maximum distance from the FAP where an UE attaches to the FAP rather than to the MBS. The performance of auto-configuration schemes is analyzed in terms of the number of mobility events (i.e., number of the handovers or their initiations) for the different FAP positions within a building. Although the distance and measurement based methods outperform simple fixed power auto-configuration scheme, the number of registered mobility events is still high and unsatisfactory (especially for the scenario if the FAP is positioned close to the house boundary). Further improvement is achieved by introduction of the self-optimization schemes.

Three self-optimization schemes are proposed in [Claussen08][Claussen09]. Generally, all self-optimization schemes aim to minimize the number of mobility events based on their measurement. Consequently, the FAP must be able to collect statistical information regarding the mobility events. The first scheme forces the adaptation of FAP's power only according to the mobility events generated by passing users. The advantage is that the number of outdoor mobility events is significantly minimized. Nevertheless, the number of indoor mobility events may be high. This disadvantage is eliminated by the second proposed self-optimization scheme when the FAP tries to minimize all mobility events. The last scheme exhaustively searches over all possible power settings and the power of FAP, during which the smallest number of mobility events occurred, is regarded as the optimum. However, this approach is not really practical and serves only as a benchmark. The numerical results demonstrate that self-optimization schemes noticeably outperform all auto-configuration methods. As already stated, the main disadvantage of all self-optimization schemes proposed in [Claussen08a][Claussen09] is that UEs inside the house are not always able to attach to the FAP as the full house coverage is not ensured.

In [Claussen08b] the authors additionally contemplate another auto-configuration scheme taking activity/inactivity of users into consideration. If no users of the FAP are currently active (no voice or data are transmitted), the transmitting power of FAP is decreased by 10 dB. At the same time, the FAP user's idle mode cell reselection threshold is decreased by 10 dB to guarantee that the UEs remain connected to the FAP. However, even with this improvement, the auto-configuration scheme is outperformed by above mentioned self-optimization schemes.

Two more power schemes, which represent the second approach, are introduced in [Choi09] and [Jo09b]. In [Choi09], the authors propose an Adaptive Coverage Adjustment (ACA) algorithm. The aim of the paper is similar to the self-optimization schemes proposed in [Claussen08a][Claussen09], i.e., to minimize mobility events and to reduce signal leakage. If the UE currently attached to the MBS is in close vicinity of a FAP, the FAP itself iteratively decreases it's transmit power as long as the passing UE is in FAP's range. After specific time period when the UE moves away from the FAP's coverage, the FAP increases power to the initial value. Nevertheless, this scheme is not able to fully mitigate the redundant handovers since the decrease of power is done after reception of handover request at the side of FAP. In [Jo09b], self-optimization scheme allowing the FAP to adaptively adjust transmitting power is presented. The proposed scheme is composed of two steps. In the first step, the self-configuration of the FAP's transmitting power is accomplished. In the second step, the adaptation of current transmitting power according to radio environments obtained by measurements is performed. The aim of the authors is like as described in [Claussen08a][Claussen09], i.e., to minimize interference caused by the FAP to passersby users while to achieve sufficient indoor coverage. However, the authors do not use the number of generated mobility events but consider leakage of the FAP's signal for its power adaptation.

2.3 Multimedia Broadcast Multicast Services (MBMS)

The concept of delivering multimedia services in either broadcast or multicast mode was introduced in term of Multimedia Broadcast and Multicast Services (MBMS) in 3GPP standard and Multicast Broadcast Services (MBS) in IEEE 802.16 standard. The MBMS is standardized to support GERAN, UTRAN and E-UTRAN while MBS is standardized to support mobile WiMAX network. The current status of either MBMS or MBS will be described from current standardization, latest research related to MBMS/MBS procedures and commercial implementation of MBMS.

The MBMS was introduced in the Release 6 of Universal Mobile Telecommunication System (UMTS) in order to deliver multimedia data from a single source entity to multiple destinations. As the evolutions in 3GPP rolls, E-MBMS is already included in the Release 9 of Long Term Evolution (LTE). The 3GPP standardized the reference architectures and control procedures for MBMS in UTRAN and its evolutions in EUTRAN. The E-MBMS appears in 3GPP standardization [3GPP TS 36.300 V8.4.0 (2008-03)] which describes some new features such as MBMS/Unicast-mixed cell, MBMS-dedicated cell, single cell transmission, and multi cell transmission including MBSFN (Multimedia Broadcast Single Frequency Network).

The MBS is introduced in IEEE specification 802.16 for mobile WiMAX. The IEEE approach for Multicast Broadcast Service specifications covers the establishment of MBSs, Inter-MBS Zone transition, which allows seamless transition from one MBS Zone to another without any interruption of MBS data service, performance enhancement using Macro Diversity, efficiency power control consumption and Multicast and broadcast zone (MBS_Zone), Multicast and Broadcast Service support, Multicast and Broadcast Service Management [IEEE Std 802.16™-2009].

Although both standardization bodies have already specified MBMS/MBS, none of them has specified the implementation of MBMS/MBS in Femtocell. Beside standards, MBMS/MBS has become a very potential research topic in wireless engineering. Research of novel mechanism for efficient radio bearer selection during E-MBMS transmissions in LTE networks was described in [Alexiou 2009]. The mechanism to efficiently deliver multiple E-MBMS sessions, investigation of point-to-multipoint (PTM) transmission supporting Adaptive Modulation and Coding (AMC) as well as retransmissions based on incremental redundancy were introduced in [Anh Phan 2009] and [Lopes 2010]. Performance evaluation of MBMS in LTE framework by a simulator set up according to 3GPP standard was presented in [Zhang 2009]. Proposed signaling architecture for multicast/broadcast services exploiting the MBS specification in the Mobile WiMAX standard are described in [Femminella 2010]. Energy-efficient cooperative multicasting scheme for Multicast Broadcast Multimedia Services (MBMS) offered by WiMAX by properly selecting Relay Agents (RAs) based on their location and channel condition was proposed in [Elrabiei 2010]. A proposed method to allocate radio resource units in overlapping MBS Zones was introduced in [Cheng 2009]. Cheng proposed radio resource allocation and re-allocation algorithms to minimize the number of re-allocated resource unit due to the change of MBS Zones topology. Other research describes Multilevel Coupling Modulation for Multi-Resolution Multimedia Broadcast Multicast Service in OFDM Systems as described in [Yuh-Ren Tsai 2011]. The implementation case of MBMS is measure in Performance Evaluation of Cellular Networks Offering TV Service by [Rong 2011a]. Research on Resource Allocation in Multi-cell MBMS Single Frequency Networks was introduced by [Jiang 2010]. Study on Layered Algorithm for Cooperative MBMS Enhancement was described in [Santos 2010].

Besides standards and research above, there are some cases of deployment trial of MBMS. Ericsson had completed the world's first live MBMS trial in 2006 which was described in [Ericsson07]. As described in [3G08], Huawei Technologies and Qualcomm announced the completion of Europe's first MBMS (Multimedia Broadcast Multicast Service) field trial, carried out in conjunction with Telecom Italia. This trial represents a significant milestone in the development of the solution.

2.4 Identification of femtocells

When introducing a new base station into the network, a Physical Cell Identity (PCI) needs to be assigned for each of its supporting cell. Several solutions were proposed recently for the classical macro cell scenario [R3-080812] to try to solve the collision/confusion issue but none of them really addresses the femto cell scenario.

1) Randomized PCI selection

The simplest method consists of randomly selecting the PCI among the possible values. However, this approach does not address the collision/confusion issue and leads to serious problems in the network that are difficult to detect, but it is applicable at least to the deployment of isolated cells.

2) PCI selection after radio environment scanning

This method relies on the capability of the MBS to scan its radio environment before starting to operate, at least in terms of reception of the downlink transmission band of eventual neighbouring radio cells, in the frequency band where it intends to establish its own cell(s). The scanning phase helps the MBS to identify potential intra-frequency neighbour cells and thus avoid a collision in the selection of the PCI for its own cell. In order to perform a confusion-free selection, the MBS needs to receive the necessary information on the neighbours.

While this method addresses both, collision and confusion, there are no guarantees that they are always fulfilled. Moreover, depending on the deployment and antenna tilting, the "visibility" between MBSs might be significantly different than the neighbour cells to be measured by the terminals (in the streets, etc.). To that extent, the reasons why this method was discarded for ANR (Automatic Neighbour Relation) are also the same making us doubting on its validity for the femto use case.

3) PCI selection after the use of temporary identifier

This approach relies on the use of a temporary PCI for a configuration phase during which the MBS, supported by UEs in the cell, identifies intra-frequency neighbour cells and thus avoids a collision in the selection of the PCI for its own cell.

In order to perform a confusion-free selection, the MBS needs to receive the necessary information on the neighbours.

While this method addresses both requirements, there are no guarantees that they are always fulfilled. Moreover, it depends both on the availability of UEs to apply this method, and on the proper location of the UE to identify each of all of the neighbours.

4) PCI assignment by means of a central function "GeoiLoc"

This method relies on a central function that stores information about MBSs, their accurate or at least approximate location, their supported cells and the related configuration such as the PCI.

Assuming that the location of the MBS is available (e.g., via GPS), the centralized entity, GeoiLoc, can via simple distance calculations automatically provide an optimum PCI assignment to the newly introduced MBS. This geo-location method (actually corresponding to the transmitting antenna(s) supporting the considered cell) does not need a high accuracy, in fact, for an optimum selection/assignment of the PCI, it is enough to have a coarse distinction on where a MBS is placed with respect to others.

The geo-location of the MBS may be of coarse accuracy or based on other types of information, e.g., information obtained by applying ad.2) or ad.3) and resulting in the identification of some few neighbours. While this information is insufficient for proper geo-location, it is certainly sufficient for proper PCI assignment.

5) PCI assignment by means of network rollout planning

In traditional network rollout and configuration methods, the PCI is properly configured according to the identified requirements, as part of the other parameters of a cell, by means of a network planning tool. Commercial network planning tools usually provide an automatic function for the proper assignment of the PCI.

The MBS(s) and the antenna(s) also need to be properly geolocated, while the geolocation accuracy required by a network planning tool is far higher in order to properly configure the whole range of radio parameters.

Network planning related to a new cell needs to be taken in advance, and the obtained configuration data are either stored in the MBS before its installation or loaded (via O&M or locally) after the physical installation and before being put in operation.

2.5 Authorization procedure

2.5.1 Access of visiting users to closed FAP

A solution for enabling an access of visiting UEs to a FAP with closed access is presented in [Qualcomm10]. The authors propose how to handle the closed FAP entry by the visiting UEs in operator's core network. The solution is based on configuration of records stored in operators CSG (Closed Subscriber Group) list server. This configuration requires advanced modification of the FAP via a control interface. This limits utilization of such approach for users with limited computer skills. Moreover, authors define only general framework of the procedure focusing on core networks management and do not discuss, for example, details on initiation of access of closed FAP by visitors or authors do not discuss definition of visiting UEs right and responsibilities (e.g., related to billing, legal issues, etc.).

2.5.2 Emergency call

Emergency calls are processed in two different cases, CSG (Close Subscriber Group) and OSG (Open Subscriber Group).

Considering the OSG, the UE knows about all near cells. Emergency calls are included in RRC (Radio Resource Control) connection establishment by *RRCConnectionRequest* message in the field *establishmentCause*, value “emergency” as addressed in [3GPP TS 36.331] and [3GPP TS 36.331 V 10.3.0]. RRC connection establishment procedure switches the UE from RRC_IDLE mode to RRC_CONNECTED mode, i.e., the UE can transfer unicast data to/from UE. All differences of individual functions between RRC_CONNECTED mode and RRC_IDLE mode are described in [3GPP TS 36.331 V 10.3.0], page 19-20. The UE initiates the RRC connection establishment procedure when upper layers request establishment of an RRC connection while the UE is in RRC_IDLE. One of the described requests is emergency call. The conditions of access to the cell are also presented. The access is not barred mainly if: *ac-BarringForEmergency* is set to *TRUE,* Access Classes 10 and the relevant Access Class (11 to 15) are not barred [3GPP TS 22.011], *ac-BarringForSpecialAC* is set to *zero.* Messages *RRCConnectionRequest, RRCConnectionSetup and RRCConnectionSetupComplete* do not include CSG information.

Considering the CSG, the UE knows only about the limited number of cells, which are identified in the whitelist of UE. The whitelist contains one or more CSG Identities (a unique numeric identifier) associated with the CSG cells on which the UE is allowed access. The CSG whitelist is maintained and provided by NAS (Non-Access Stratum). The CSG Identities are broadcasted by the cells.

The CSG is addressed in [3GPP TS 25.367], [3GPP TS 24.285] and [3GPP TS 22.220]. The [3GPP TS 25.367 10] describes CSG Identification, CSG Selection, CSG Cell Reselection and CSG and Hybrid Cell Handover. CSG Identity or CSG ID is a unique numeric identifier. UE belonging to a CSG has the corresponding CSG ID in its CSG whitelist. The CSG whitelist is maintained and provided by NAS. The CSG ID is broadcasted in system information by the CSG cell or hybrid cell, and used by the UE for cell (re)selection and handover purposes. CSG Selection is described in the meaning of manual CSG ID selection by human user. CSG Cell Reselection presents measurement rules for CSG cells, reselection to/from/between CSG Cell(s). CSG and Hybrid Cell Handover focuses on handover from/between CSG Cell(s). It also describes CSG/Hybrid cell intra-frequency measurement procedure and CSG/Hybrid cell inter-frequency/inter-RAT measurement procedure of handover to CSG/Hybrid cell.

The [3GPP TS 24.285] presents allowed CSG list management object, which is used to manage the list of allowed CSG IDs, the Operator CSG IDs and the related restricted access information at UE. The [3GPP TS 22.011] denotes Access Control including Access Classes description and emergency calls. The [3GPP TS 22.220] describes common requirements including access control requirements and display requirements for CSG. It also mentions H(e)NB shall support emergency calls for both CSG and non CSG members as specified in [3GPP TS 22.101]. The [3GPP TS 22.101] denotes emergency calls from service aspects point of view: identification of emergency numbers, emergency calls in the CS/PS/IM CN domain, general requirements, etc.

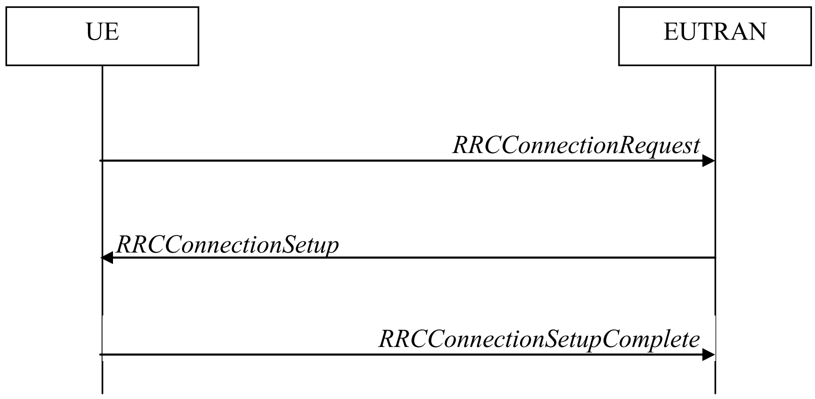


Figure 1. RRC connection establishment [3GPP TS 36.331]

The [3GPP TS 36.331 V 10.3.0] also describes RRC connection establishment procedure. It also denotes System information acquisition procedure, which ensures acquiring the AS- and NAS- system information that is broadcasted by the E-UTRAN. This information also includes CSG in *SystemInformationBlockType1*: *cellBarred* (cell is barred), *cellReservedForOperatorUse* (as defined in [3GPP TS 36.304]), *csg-Identity* (Identity of the Closed Subscriber Group the cell belongs to), *csg-Indication.* If set to TRUE, the UE is only allowed to access the cell if it is a CSG member cell or if selected during manual CSG selection. The importance of System information acquisition procedure or its execution is seen from its description: "The UE shall apply the system information acquisition procedure upon selecting and upon re-selecting a cell (e.g., upon power on), after handover completion, after entering E-UTRA from another RAT, upon return from out of coverage, upon receiving a notification that the system information has changed, upon receiving an indication about the presence of an ETWS (Earthquake and Tsunami Warning service) notification, upon receiving an indication about the presence of a CMAS (Commercial Mobile Alert System) notification, upon receiving a request from CDMA2000 upper layers and upon exceeding the maximum validity duration." This procedure is performed more than, e.g., handover. If the UE is in OSG, the [3GPP TS

36.331 V 10.3.0] therefore completely describes the authorization procedure in the case of emergency calls for OSG case.

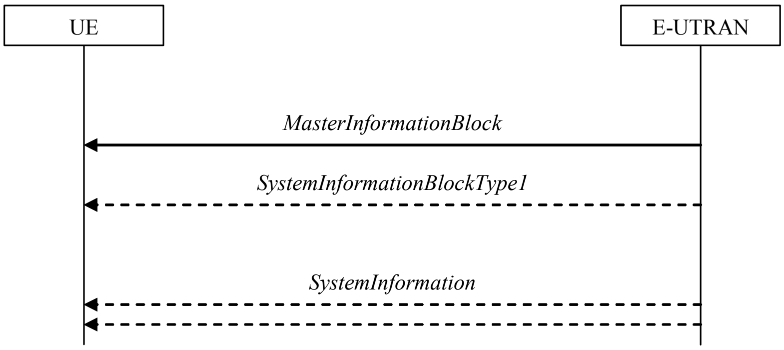


Figure 2. System information acquisition [3GPP TS 36.331]

The [3GPP TS 27.007] describes AT commands also related to emergency calls. These commands are processed in the UE between MT (Mobile Termination) and TA/TE (Terminal Adaptor/Terminal Equipment). It describes pending commands while emergency call is in process, i.e., it enables not to use SIM PIN or SIM PUK.

2.6 Backhaul Aware Scheduling

The study of WiMAX 802.16e backhaul is addressed in [sayenko08]. According to the paper that the scarcity in backhaul will be happened when over provisioning is not possible. In this case, if real-time traffic is not given higher priority over non-real-time traffic, the performance of the latter will be affected. In order to deal with the bottleneck, a well-known IP traffic management such as DiffServ is proposed. The service classes of WiMAX data transfer are mapped into different DiffServ traffic classes. While Expedited Forwarding (EF) is mapped into WiMAX real-time traffic classes (ERT-VR, RT-VR), Assured Forwarding (AF) is used for Best Effort traffic classes. By using DiffServ, the delay of VoIP traffic is maintained low (compared with BE traffic for the same backhaul profile) even though the backhaul load increase. It is observed in the paper that admission control considering the bottleneck backhaul link will lead into more efficient use of the scarce backhaul capacity [Lakkakorpi2010].

Lakkakorpi in [Lakkakorpi2005] and [Lakkakorpi2010] proposed adaptive Connection Admission Control (CAC) for DiffServ traffic classes. The admission control decision is based on link load measurements and reservation information for individual traffic classes. In order to enable such capabilities, traditional bandwidth broker framework is modified. DiffServ router will apply different admission control rules for different connection types. Packet scheduling is used to protect EF traffic over AF traffic and other EF traffics. During congestion periods, non-admission controlled traffic has to adapt in order to guarantee QoS for EF traffics.

While Lakkakorpi proposed the solution how to overcome the congestion issue in macrocell WiMAX backhaul, Chowdhury et al. proposed a dynamic service level agreement (SLA) negotiation using bandwidth broker for femtocell networks [Chowdhury09]. A new proposal is based on a SLA negotiation procedure which allows the bandwidth broker to allocate enough bandwidth for femtocell users. The reserved bandwidth is allocated dynamically based on previous femtocell calls bandwidth. Based on the historical data, the bandwidth for femtocell is calculated and reserved for upcoming calls. This scheme will allow ensuring the QoS for the real-time services of femtocells.

While both Lakkakorpi and Chowdhury et al. propose bandwidth calculation and admission control in bandwidth management entity (DiffServ router or bandwidth broker), our proposal related to admission control and scheduling is intended to be attached within FAP. This proposal is considered to support the FAP vision as self-configured device, those limiting dependency with third party nodes or expensive SLA agreement between mobile operator and ISP.

The study about backhaul aware scheduling (BAS) in femtocell is very limited to none. The scheduling and admission control will take into account the fluctuation in the backhaul. Bandwidth estimation is performed to give initial feedback to FAP whether bottleneck occurred. If the backhaul bandwidth link is far above the bandwidth request from FAP users, the existing WiMAX scheduling is used. However if the bandwidth links utilization is about 70% occupation the FAP will activate the backhaul aware scheduling. Since our approach is focused on the backhaul side rather than on the radio aspect, WiMAX (802.16e) was chosen just for study case due to its maturity. The similar algorithm can be implemented in the LTE.

3 GENERAL ASSUMPTIONS AND SCENARIOS DESCRIPTION

This section describes the general assumptions and scenarios used in the evaluation of individual topics with respect to D2.1 document [FRED2.1]. A more detail description of system models and simulation methodology is addressed individually in section 4.

3.1 Packet routing procedure

The objective of the routing studied in this deliverable is to allow transmit data directly between two UEs attached to the same FAP. Following scenarios and system assumptions are considered:

- Mobility models - Indoor mobility movement is taken from deliverable D2.1 where terraced house model based on [Claussen08] is considered. Outdoor mobility model used in the evaluations is slightly modified version of mobility model described in D2.1 designated for handover evaluations when outdoor users are moving along street.

- Path loss models - Two path loss models are assumed. To simulate path loss in indoor environment, ITU-RP.1238 model is implemented. The path loss model for outdoor environment is based on Okumura Hata empirical model. Both models are described in more detail in D2.1.

- Traffic models - Traffic from/to FUEs is generated by means of traffic models based on VoIP and FTP described in D2.1. In addition, full buffer model in sense that all UEs have always some packets to send/receive is utilized to assess maximum achieve throughput.

- FAPs and MBS deployment - Deployment of individual stations within the simulation scenario uses the slightly modified scenario for handover evaluation described in D2.1.

- Performed simulations are described for LTE(-A) system according to release 10 with TDD duplex [3GPP TS 36.211- V10.1.0 (2011-03)]. However, the general principle may be used in other contemporary technologies such as WiMAX with TDD or FDD.

- It is assumed that the FAP is able to route data between its users. Thus, the FAP does not send data farther to the FAP's gateway or operator's core network if two UEs attached to it communicates between themselves, i.e., we extend the idea proposed in the first part of routing.

- The proposal does not modify signaling route, which remains the same and may terminate at the core network of the operator.

- Both direction transmission, i.e., DL and UL, are considered.

- The FAPs and MBS use the same frequency bands.

3.2 Power control procedure

In the scope of power control, analogical assumptions and scenario are considered as in case of routing. To that end, mobility models, path loss models, FAPs and MBS deployment is the same as described in section 3.1. The differences are the following:

- Traffic models – only VoIP and FTP are taken into account.

- LTE-A FDD frame and only DL direction is assumed since we are focusing on power control of FAP, i.e., power control in DL.

3.3 Multimedia Broadcast Multicast Services (MBMS)

The MBMS offers the possibility to deliver multimedia service over wireless network effectively. In the other hand, it consumes relatively high data rate, which will affect the scarce radio resource in the network. The performance of MBMS in the Femtocell network gives opportunity to cope this challenge. In the scope of MBMS, analogical assumptions are considered as in case of packet routing. To that end, path loss models, FAPs and MBS deployment is the same as described in section 3.1. The differences are the following:

- Mobility model – in the scope of MBMS, it is assumed that there were no specific users mobility, but only used random generated users positions based on certain building layout, i.e. residential and office building. More description will be presented in section 4.

- Traffic model – Only video traffic are taken into account. Video traffic source was www.trace.asu.edu.

- LTE-A FDD with 10 MHz bandwidth

3.4 Scheduling

3.4.1 Timer based interference mitigation

Timer based interference mitigation (presented in section 5.1) has been evaluated by means of a simulation tool described in [FRED4.1], section 5.2. Similar assumptions as those described in [FRED4.1] about the simulated system have been made for this evaluation. The following assumptions are considered:

- Mobility model – Users are supposed to be static.

- Path loss model - Static path loss and shadowing models aligned to [FRED2.1] guidelines. Dynamic and frequency selective shadowing accounting for slow UE mobility, with a Doppler frequency set to 3 Hz. The channel is modeled as a 6 taps delay line with relative average power and delays for each tap being set according to ITU-R M.1225. Wall loss equal to 10 dB.

- Traffic model - The high constant bit-rate equal to 10 Mbit/s is send to all femto-attached users.

- Both outdoor and indoor terminals are deployed in a simulation area, which is served by a single MBS located in its centre. FAP sites are deployed in this area in conformance with [FRED2.1] guidelines.

- A closed subscription model has been assumed instead of an open subscription model. Indeed, downlink femto to macro interference is low enough, in case of open subscription models, so that mitigation techniques are not clearly needed in this case. On the contrary, if closed subscription model is assumed, the coexistence of both macro tier and femto tier in the same RF band raises serious interference problems that justify the use of dedicated mitigation techniques.

- Up to 32 frequency resource block can be used in the FAP.

3.4.2 Backhaul Aware Scheduling

The following assumptions are taken into consideration regarding the backhaul aware scheduling study:

- Backhaul parameter – type of transmission used is ADSL/ADSL+ with 2 Mbps downstream rate and 512 kbps upstream rate. The copper length is between 1-4 km.

- Traffic Model – traffic used in the study consist of VoIP, HTTP, and FTP with addition of Video Streaming traffic (Frame inter arrival time: 30 frames/sec and Encoder Scheme: H.264 – MPEG4). Mix traffic model from D2.1 is referred with some modifications in the proportion mix of traffic types. Each combination of traffic types creates a scenario. The scenarios will be described in section 5.2.3.

- FAP – the FAP used in the study is based on WiMAX with specific parameters described in section 5.2.3

- The performance of FAP services are evaluated based on three conditions, which incorporate the condition of background traffic from broadband users, i.e. no background traffic, 70% of background traffic and 80% of background traffic.

- The existing scheduler (without backhaul awareness) is used and compared to the performance of scheduling with backhaul awareness. In all simulations we did not consider overhead from xDSL and IPSec tunneling required by FAP systems.

4 MAC CONTROL PROCEDURES

4.1 Packet routing procedure and its optimization

The important aspect regarding femtocells is to guarantee optimal routing path of all data packets. The hierarchical LTE architecture for femtocells can be represented as shown in Figure 3. This figure represents three different places where FAPs (or HeNBs if referring to 3GPP terminology) are deployed. A first place may be either a home or a small enterprise, and hosts 3 User Equipments (UEs) and 2 FAPs. Each of the two other places includes one user equipment and one FAP.

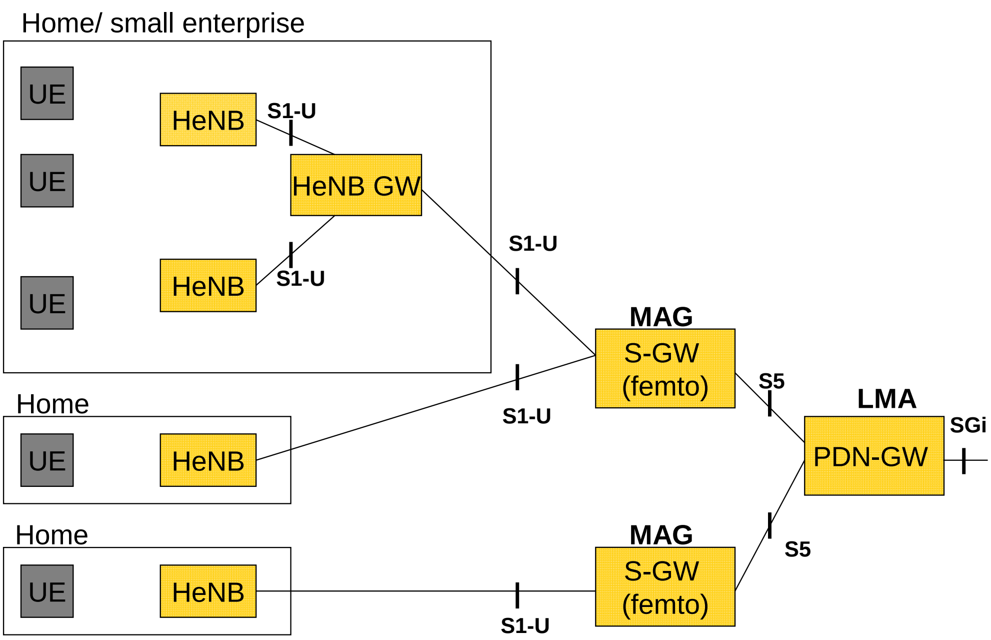


Figure 3. Hierarchical view of FAPs (HeNBs) in LTE architecture

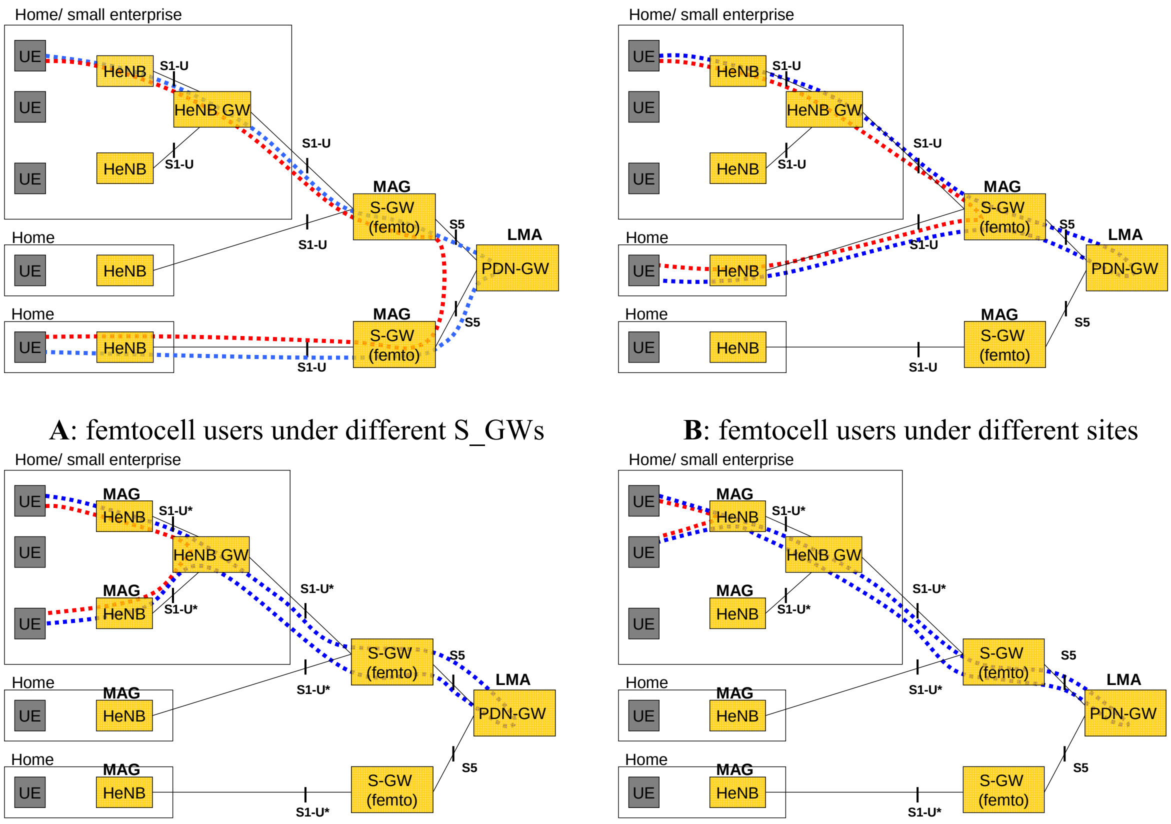
A FAP Gateway (HeNB GW) is present in the first place in order to aggregate connections from both FAPs. Then it is assumed that the 2 first places are connected toward a first Serving Gateway (S_GW) while the last place is connected to another S-GW.

Then each S_GW is connected to a PDN Gateway (PDN_GW), which is connected to the internet through the SGi interface.

The standard data path follows a hierarchical structure which is shown in blue in Figure 4. In this standard case, the PDN-GW assumes the role of a mandatory transit gateway for all user equipments under femtocell coverage.

In the standard LTE system, the PDN GW assumes a mandatory transit role whichever equipments are interconnected, whether they are under different S-GW (case A), or under the same S-GW but different sites (case B), or under the same site but different FAPs (case C), or finally under the same FAP (case D).

Advanced routing procedures have been designed in FREEDOM context, in order to achieve optimal routing as shown by the red dotted lines in Figure 4. Such techniques are presented in [FRED5.3]. However, when both UEs are covered by the same FAP, more specific routing optimization techniques can be applied, which are the subject of this section.



A: femtocell users under different S_GWs

B: femtocell users under different sites

C: femtocell users under different HeNBs

D: femtocell users under the same HeNB

Figure 4. Different routing optimizations

4.1.1 Technical background

In this section we introduce LTE-A data frame structure used later for analytical evaluations of throughput gain achieved by our proposal. In addition, we briefly describe LTE-A control mechanisms, which are further utilized in our proposal. All mechanisms and frame structure is described in compliance with [Sesia09] and [TS36.300_10.0.0].

LTE-A frame structure

In LTE-A, the data are sent in frames composed of 10 subframes with duration of 1 ms. Several frame configurations can be selected in TDD duplex. The configurations differ in amount of subframes assigned for uplink (UL) and downlink (DL). In Fig. 1, simplified TDD frame structure with configuration "1" is illustrated (this frame configuration is considered in our further evaluations). The frame consists ten subframes dedicated for either downlink (D), uplink (U), or special (S) subframes.

While the frame is divided into specific amount of OFDM symbols (n_{SMB}) in time domain, certain amount of subcarriers (n_{SC}) is contained in frequency domain. The LTE-A frame consists specific amount of resource elements (REs), which number can be expressed as:

$$n_{REpF} = n_{SC} \times n_{SMB} \tag{1}$$

As Figure 5 shows, not all REs are primarily dedicated for DL or UL transmission as some radio resources are spent for transmission of signaling and control information. Thus, the number of all REs in *k-th* frame can be rewritten as:

$$n_{RE} = n_{OH}^{k} + n_{D,DL}^{k} + n_{D,UL}^{k} + n_{free}^{k} \quad (2)$$

where n_{OH}^{k} stands for number of REs carrying signaling overhead, $n_{D,DL}^{k}$ and $n_{D,UL}^{k}$ represents the amount of REs transporting DL and UL data, and finally n_{free}^{k} corresponds to the number of REs that are unoccupied. As long as $n_{free}^{k} > 0$, all data can be transmitted within the frame and no restriction has to be applied. The number of REs assigned to the transmission in *k-th* frame ($n_{D,k}^{k}$) is directly proportional to the amount of data transmitted within the frame ($\delta_{D,x}^{k}$) since:

$$n_{D,k}^{k} = \frac{\delta_{D,x}^{k}}{\Gamma_{D,x}^{k}} \quad (3)$$

where $\Gamma_{D,x}^{k}$ stands for transmission efficiency. It represents the amount of data transmitted in a RE in dependence on the quality of channel between transmitting and receiving station.

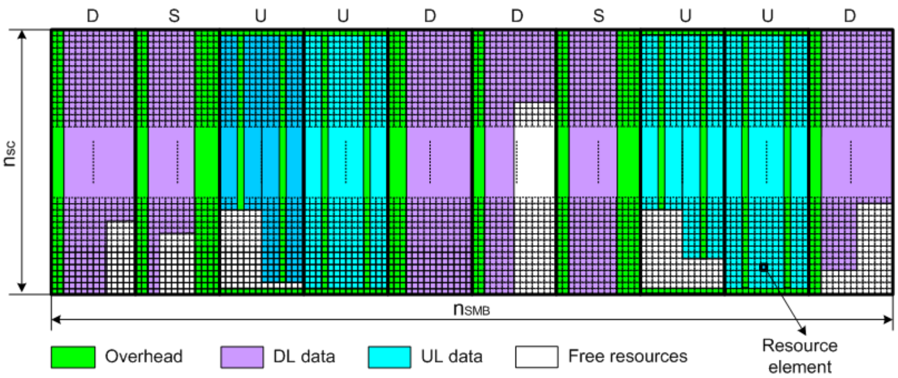


Figure 5. LTE-A frame structure with TDD configuration "1"

LTE-A control layer mechanisms

Signaling and control information are conveyed via DL and UL control channels in LTE-A. In DL, the signaling is transmitted through Physical Downlink Control Channel (PDCCH), Physical Control Format Indicator Channel (PCFICH), and Physical Hybrid ARQ Indicator Channel (PHICH). The PDCCH usually carries several Downlink Control Information (DCI) messages with different formats depending on the transmitted control information. Similarly, control information is transmitted via Physical Uplink Control Channel (PUCCH) and Physical Random Access Channel (PRACH) in UL direction. The LTE-A standard defines several PDCCH and PUCCH formats carrying control signaling information [16]. In our proposal, several LTE-A procedures utilizing above mentioned control channels are exploited: i) request for UL resources, ii) grant in UL, iii) assignment of DL resources, iv) channel estimation, and v) Hybrid Automatic Repeat reQuest (HARQ) process.

If any data are prepared to be sent by the UE in UL, the UE needs to send a request for allocation of radio resources. To that end, the UE transmits to the MBS so called Buffer Status Report (BSR) indicating the amount of data that has to be transmitted in UL. If a UE does not have enough resources allocated in UL to send BSR, two options may be followed. The first option is to send single-bit Scheduling Request (SR) over PUCCH. The second option is to perform Random Access Procedure (RAP) by means of PRACH to request sufficient UL resources, which are further utilized for sending BSR.

To transmit data in Physical Uplink Shared Channel (PUSCH), the MBS has to issue a grant for this transmission. The grant is sent in DL through the PDCCH. The grant delivers information such as the size of resource block grant, power control command, or Modulation and Coding Scheme (MCS) to the UE. The MBS can use either "dynamic" scheduling or "persistent" scheduling. The former one is efficient for bursty traffic dynamic in rate while the latter one enabling allocation for longer period than one subframe. If the MBS transmits data to the UE in DL, it has to inform the UE of such resource allocation. This information is sent also in PDCCH. If the current channel quality needs to be known, channel measurement and estimation has to be performed. In LTE-A, the channel measurement and estimation is accomplished via of so called Reference Signals (RSs). The RSs are transmitted in both DL and UL directions and it carry no useful information for users. The results of channel measurements are transmitted through a Channel Quality Indicator (CQI) feedback. The CQI feedback contains the information on MCS, which can be utilized by the UE to achieve block error rate above certain threshold. The CQI feedback is sent in PUCCH.

To correct erroneous packets received at a MBS or at a UE, a HARQ is introduced in LTE-A. According to [16], time between transmission of original data and transmission of positive acknowledgement (ACK) or negative acknowledgement (NACK) lasts approximately 8 ms. Thus, in case of unsuccessful transmission, data retransmission lasts usually little longer than 8 ms due to scheduling. Whether the MBS receives data correctly in UL is indicated via PHICH. The UE transmits ACK/NACK via PUCCH.

4.1.2 Efficient indoor data routing

If two UEs currently attached to the same FAP communicate between themselves, data must be transmitted two times via radio interface (see Figure 6). In the first step, the data are sent from the UE1 to the FAP. In the second phase, the FAP relays data to the UE2. As this approach waste radio resources we propose to route data directly whenever direct communication consumes less radio resources. In other words, when the UE1 and UE2 are not within communication distance, data are sent similarly as in conventional approach (note that by conventional approach we mean already optimized routing according to, e.g., [Chiba09]). However, if the channel quality between UE1 and UE2 becomes sufficient (due to UE's movement), the former routing path could be changed to the direct one as depicted in Figure 6. Still, if the UE is going to sent only small amount of data that could be transmitted within one frame, the conventional procedure is performed notwithstanding (e.g., if UE has some bursty traffic). In this case, the selection of proper routing path would be useless since the calculation of proper path lasts longer than data transmission itself. Nevertheless, if UE asks for more radio resources (FTP, streaming video, etc.) than the FAP is capable to serve within a frame, the proposed procedure takes place instead of conventional one.

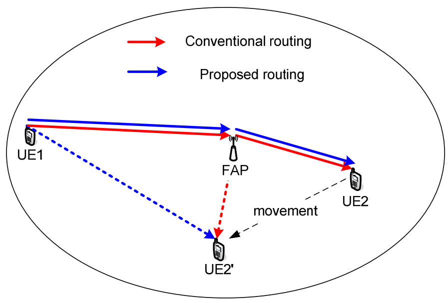


Figure 6. Data routing between two UEs connected to the same FAP

The following two subsections describe the control procedure for conventional routing strategy and further its necessary enhancements to support direct communication between two UEs.

Conventional routing of data within the FAP

The conventional control procedure is rather simple as depicts Figure 7. The UE1 has data intended for the UE2. Consequently, UE1 sends scheduling request to the FAP in order to get allocation of radio resources in UL direction. To request UL radio resources, a BSR is issued as described in the previous section. After the FAP receives the scheduling request, it can either grant or deny the request through PDCCH channel. If the grant is acknowledged, the UE1 can transmit its data to the FAP at scheduled interval(s). As soon as data are received by the FAP, data are processed and checked for transmission errors. If data are received correctly, the FAP sends acknowledgment of their correct reception. Simultaneously, the FAP determines if the data should be sent further to the network or if the data should be retransmitted to another UE also connected to it. In the latter case, the FAP assigns radio resource for the UE by means of a message in PDCCH. Subsequently, data are transmitted and acknowledged via PUCCH.

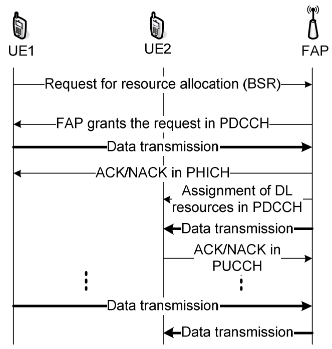


Figure 7. Control procedure for conventional data routing

It is clear that above mentioned transmission process is ineffective since identical data have to be transmitted two times. As a result, the radio resources are wasted and FAP's throughput can be negatively affected especially at heavy traffic loads.

Proposed routing of data within the FAP

The proposed control procedure is shown in Figure 8. Similarly as in conventional procedure, the UE asks for radio resource allocation in UL. As a response, the FAP dedicates required amount of radio resources to manage data transmission. From now on, the UE1 starts transmit its data to the FAP similarly as in the conventional case. At the same time as the grant is sent to UE1, the FAP orders the UE2 to measure the signal quality received from the UE1, i.e., the UE2 has to estimate the quality of channel between the UE2 and currently transmitting UE1. The FAP's request message is sent through PUCCH channel (content of all new proposed messages is discussed in the next section). The channel quality between UEs needs to be measured to allow the FAP to select appropriate path for data routing. Note that user's data from UE1 to UE2 are still transmitted via FAP during measurement.

After the UE2 performs the measurements, the results are conveyed to the FAP via CQI feedback. At this stage, the FAP has to estimate whether the direct transmission or transmission through the FAP is more efficient. To select the best routing path, the FAP must take into account the quality of all involved routes. Besides the channel quality between both UEs, the state of other two channels (from the UE1 to the FAP and from the FAP to the UE2) must be known to the FAP. The channel quality between the UE1 and the FAP is known since the FAP receives data from the UE1 in the meantime. Similarly, the channel quality between the FAP and the UE2 is known as the UE2 reports channel quality periodically to the FAP to select suitable MCS in DL direction.

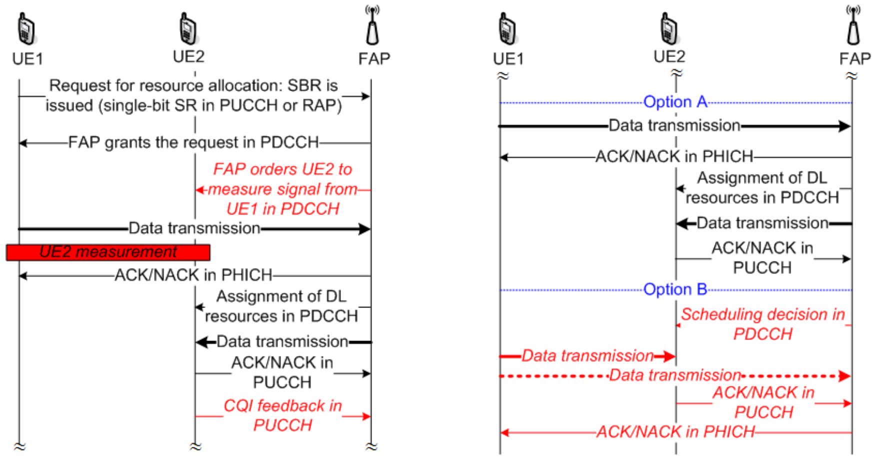


Figure 8. Control procedure for proposed data routing. The suggested enhancements are distinguished by red italics text.

Based on the measurement, the FAP determines the optimal path between both UEs. The calculation of proper route can be done according to several metrics. For this purpose, we use so called Radio Resource Cost (RRC) metric [Becvar09]. This metric calculates the amount of radio resources that has to be assigned for transmission of certain amount of data via all possible routes. Since LTE-A is considered, the RRC evaluates the Number of Resource Blocks (NRBs) between station *x* and station *y* necessary to be allocated for data transmission as:

$$NRB_{x-y} = ceil\left(\frac{D}{\Gamma_{x-y} \times n_{REpRB}}\right) \qquad (4)$$

where *ceil(.)* means rounding to the closest upper integer, *D* corresponds to the amount of data transmitted between station *x* and station *y*, n_{REpRB} stands for the amount of REs per one RB, and Γ represents the transmission efficiency determined according to MCS (see (3)). The FAP selects the path in accordance to the following:

$$\begin{aligned} &path = i \middle| P_i = \min\{P_1, P_2\}; \\ &P_1 = NRB_{1hop} + NRB_{2hop}; P_2 = NRB_{direct} \end{aligned} \qquad (5)$$

Immediately as the proper path is selected, the FAP either continues to retransmit UE1's data to the UE2 (in Figure 8 labelled as "Option A") or sends new decision in PDCCH to unify UE2's receiving intervals with UE1's transmission intervals (in Figure 8 labelled as "Option B"). Still, the acknowledgment of successful/unsuccessful reception is sent to the FAP rather than to the UE1. The reason is that the UE1 is not aware of "shorter" routing path and expects to receive ACK/NACK from the FAP. Subsequently, the FAP retransmits the acknowledgement to the UE1. As long as the UE1 transmits data to UE2, the FAP has to be continuously aware of the quality of individual involved paths in order to adaptively select the appropriate routing path. The path may change during the UE1's transmission, if necessary, from one hop to two hops and vice versa.

When the UE2 receives data directly, the FAP has to receive transmission from UE1 notwithstanding since the FAP should at least decode potential control information embedded in PUCCH. In addition, data received at the FAP does not have to be discarded immediately. The FAP could wait for specified time whether ACK from UE2 relating to the correct reception of data is obtained. If data are successfully received by the UE2, the FAP discards data. On the other hand, if the data are delivered at the side of UE2 with errors or not at all, the FAP itself retransmits the lost data to UE2 without intervention of UE1. Consequently, the robustness of the overall transmission is improved by the proposed technique since the lost of data at the FAP or UE2 does not mean necessarily retransmission by the UE1. Thus, not only FAP radio resources are saved but also packet delay is further minimized.

Implementation aspects of the proposal

To implement our proposal, several new messages mentioned in previous sub-section have to be specified. The purpose of the first message is to order the receiving UE to additionally estimate channel quality between this UE and currently transmitting UE. We propose to send the message in PDCCH with new DCI format "4", which informs the UE of the exact time and frequency at which the UE is transmitting. If the UE receives this message, it estimates channel quality with help of RSs transmitted in UL. Consequently, only location of RSs within the data transmission needs to be known to receiving UE.

The CQI feedback containing measurements of channel quality between UEs is sent in PUCCH with new format "2C". The structure of the message can be the same as the conventional format "2" used for sending the conventional CQI feedback.

The objective of the third message is to convey new scheduling decision from the FAP to the receiving UE. In other words, the message informs the UE that data will be received at different time and frequency. The message can be sent in PDCCH with new format "1E". The FAP scheduler also has to take into consideration that receiving UE needs sufficient time to switch its antenna from receiving (transmitting) to transmitting (receiving) mode if the receiving UE intents to send its own data in UL. In addition, the UE must be aware of different data layout within UL and DL subframes (e.g., RSs location).

To support proposed above-mentioned changes, the UE's and the FAP's firmware has to be slightly modified. While the UE needs to know only above mentioned messages, the FAP has to be able to calculate appropriate routing. This, however, can be easily accomplished since the routing path is simply estimated from reported CQI.

Signaling overhead of the proposed routing procedure

The signaling overhead introduced by the proposed routing contains three messages described in the previous section. The overhead generated by the ordering the UE measure signal quality is negligible since the command is sent only once at the beginning of UE's transmission. Similarly, the overhead introduced by message conveying new scheduling decision could be neglected as this message is sent only if the routing path is changed. This occurrence happens only infrequently since the UEs are mostly nearly stationary indoor. Consequently, the only measurable overhead introduced by the proposed procedure is due to reporting of CQI. The amount of REs dedicated for reporting in one frame can be expressed as follows:

$$n_{OH}^{p} = \sum_{i=1}^{n} n_{ro} \times a_i \times \frac{t_f}{t_i} \quad (6)$$

where n corresponds to the number of users attached to the FAP, n_{ro} represents the amount of REs necessary to report CQI of one antenna, a_i stands for number of antenna of *i-th* UE, t_f is frame duration, and t_i represents reporting period of the user i.

Still, the overhead generated by the CQI reporting is not significant for the femtocells. Firstly, the number of users attached to the one FAP is very limited. In most cases, up to four users are supposed to be active at the same time [Chandrasekhar08]. Secondly, one CQI report is carried only via several REs depending mostly on the amount of antenna [Sesia09], which is negligible in comparison to the number of REs per frame. Thirdly, the reporting period is proportional mostly to the speed of users and frequency of channel conditions changes. The users located within building could be assumed to move very slowly (up to 1 m/s) or to be fixed. Thus, the reporting could be done relatively infrequently and could be set to higher values such as 80 or 160 ms (according to [Sesia09] reporting period could be set between 2 to 160 ms in LTE-A).

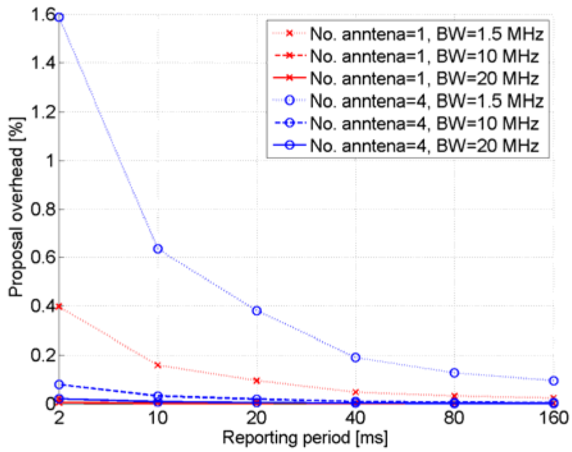


Figure 9. Reporting overhead due to the proposed routing procedure

Figure 9 depicts the reporting overhead for the worst case scenario when four users are exchanging data among themselves. The reporting overhead is negligible (hundredths of percent) if the reporting period is set to 80 or 160 ms even if low bandwidth (BW = 1.5 MHz) is allocated to the FAP.

4.1.3 Numerical analysis

Whether the proposed scheme performs better than the conventional scheme is numerically analyzed in terms of throughput gain and packet delays.

Throughput gain

To asses the throughput gain, the amount of REs carrying signalling overhead and data have to be derived for both routing strategies. Hence, we can modify (2) and take into account that two UEs within the same FAP are communicating with each other. For conventional scheme, (2) can be rewritten as follows:

$$n_{RE}^{c} = n_{OH}^{c,k} + n_{D,ULo}^{c,k} + n_{D,DLo}^{c,k} + n_{D,ULi}^{c,k} + n_{D,DLi}^{,c,k} + n_{free}^{,c,k} \qquad (7)$$

where $n_{D,ULo}^{k} / n_{D,DLo}^{k}$ is the amount of REs reserved for data transmitted to/received from the UE "outside" of the FAP and $n_{D,DLi}^{k} / n_{D,ULi}^{k}$ corresponds to the quantity of REs carrying data transmitted only for UEs "inside" the FAP. Data are labeled as "outside" if source and destination stations are not connected to the same FAP. On the other hand, by "inside" is meant that source and destination stations are attached to the same FAP. In case of the proposed scheme, (2) can be modified as:

$$n_{RE}^{p} = \begin{cases} n_{OH}^{k} + n_{OH}^{p,k} + n_{D,ULo}^{p,k} + n_{D,DLo}^{p,k} + n_{D,DLi}^{p,k} + n_{free}^{p,k}, & 1 \;\; hop \\ n_{OH}^{k} + n_{OH}^{p,k} + n_{D,ULo}^{p,k} + n_{D,DLo}^{p,k} + n_{D,DLi}^{p,k} + n_{D,DLi}^{p,k} + n_{free}^{p,k}, & 2 \;\; hop \end{cases} \tag{8}$$

As long as $n_{free}^{k}(c) > 0$, no throughput gain is achieved since all data can be transmitted also by using the conventional case. Nevertheless, the higher ratio of the frame is utilized in comparison to the proposed scheme and thus the FAP is more susceptible to overloading. If $n_{free}^{k}(c) = 0$, the throughput gain *G* achieved in *k-th* frame can be obtained by subtraction of (7) and (8) and if we take (3) into account as:

$$g^{k} = \begin{cases} \left[\left(n_{D,ULi}^{c,k} + n_{D,DLi}^{c,k}\right) - \left(n_{D,ULi}^{p,k} + n_{OH}^{p,k}\right)\right] \times \Gamma^{k}, & 1 \;\; hop \\ -n_{OH}^{p,k} \times \Gamma^{k}, & 2 \;\; hop \end{cases} \tag{9}$$

The throughput gain in (9) expresses the actual amount of bits that can be additionally transmitted in *k-th* frame if our proposal is introduced. If the direct (one hop) transmission is feasible, the throughput gain is guaranteed since direct route is used only if $n_{D,ULi}^{c,k} + n_{D,DLi}^{c,k} > n_{D,ULi}^{p,k}$. If two hop transmissions take place, the amount of REs dedicated for "indoor" data is the same for both routing schemes. Hence, the overall throughput is marginally decreased by the overhead generated by our proposal (see Figure 9).

Another factor necessary to be taken into account is the erroneous character of wireless transmissions. In other words, certain amount of data packets needs to be retransmitted due to their unsuccessful reception. Hence, the throughput gain is influenced by this fact as follows:

$$g^{k} = \begin{cases} \left(n_{D,ULi}^{c,k} + n_{Dr,ULi}^{c,k} + n_{D,DLi}^{c,k} + n_{Dr,DLi}^{c,k} - n_{D,ULi}^{p,k} - n_{Dr,ULi}^{p,k} - n_{OH}^{p,k}\right) \times \Gamma^{k}, & 1 \;\; hop \\ -n_{OH}^{p,k} \times \Gamma^{k}, & 2 \;\; hop \end{cases} \tag{10}$$

where $n_{Dr,DLi}^{x,k} / n_{Dr,ULi}^{x,k}$ is the amount of REs occupied by retransmitted data in DL/UL. As a consequence, the throughput gain achieved by our proposal is slightly increased since:

$$n_{Dr,ULi}^{c,k} + n_{Dr,DLi}^{c,k} > n_{Dr,ULi}^{p,k} \tag{11}$$

The throughput gain reached during one transmission session (e.g., time during which the FTP file is transmitted between two UEs) can be quantified as follows. We denote duration of one data transmission session as k_t. It is expressed in the number of frames during which the transmission occurs. In addition, we define the set of throughput gains per individual frames in the case of direct transmission as $G_1 = [g_1^1, g_1^2, ..., g_1^{k_1}]$ and the set of throughput gains per individual frames in the case of two hop transmission as $G_2 = [g_2^1, g_2^2, ..., g_2^{k_2}]$. Note that k_1 corresponds to the quantity of frames while direct transmission occurs and k_2 stands for the amount of frames whilst the two hop transmission is in progress (i.e., $k_t = k_1 + k_2]$). Now, the overall throughput gain can be expressed as a sum of individual partial gains:

$$G = \sum_{l=1}^{k_1} g_1^l + \sum_{m=1}^{k_2} g_2^m \tag{12}$$

Achieved throughput gain is dependent on the amount of traffic generated only “indoor” and on individual duration of one and two hop transmissions. This is analytically shown in Figure 10 where comparison of the conventional scheme with our proposal is addressed. The offered traffic is calculated for one FAP with two UEs transmitting data between themselves. To that end, bandwidth allocated to the FAP equals to 20 MHz. The position of transmitting UE and the FAP are supposed to be fixed while two positions of receiving UE are considered. One position corresponds to the scenario when direct transmission is more appropriate while the second positioned represents the case when two hop transmission is more efficient. The positions of individual stations are selected so that the CINR values between stations (both for direct and two hop transmission) corresponded to average CINR values observed farther in the simulations.

The purpose of the Figure 10 is twofold. Firstly, the goal is to analyze the impact of the ratio of UL “indoor” to UL “outdoor” traffic. In Figure 10, UL_i=100% means that all traffic generated by one UE is retransmitted to the other UE within the same FAP. On the other hand, UL_i=25% corresponds to the fact when only 25% of UL data are transmitted “indoor” while the rest of data is sent outside the FAP. Secondly, the goal is to investigate the effect of ratio between one and two hop transmissions.

The results indicate that our proposal performs always better than the conventional one. The scenario with no errors in packet transmission (i.e., PER=0%) is depicted in the left part of Figure 10. Note that the case when $k_2=k_t$ is not investigated since the results are analogical to conventional scheme as data are sent via two hops. The most notably gain is observed if all data are transmitted directly in the case of our proposal (i.e., $k_1=k_t$). If the direct transmission cannot be applied all the time (i.e., when $k_1=k_2$ and k_1/k_{t2}=0.33), the performance of our proposal is decreased. However, the results are still better in comparison to the conventional scheme. If the UL “indoor” traffic decreases, the performance of both schemes increases since some data does not have to be transmitted two times (once per a hop). Although, this is mainly for the benefits of the conventional scheme, the proposal still performs better. This implies that our proposal is profitable especially for scenarios where all traffic designated for inbound users.

Furthermore, if packet error rate is increased, the performance of our proposed scheme is not that negatively affected when compared to the conventional scheme. This is true especially if direct transmission is utilized most of the time since the probability of packet errors in UL direction is lowered (packets are transmitted only via one hop).

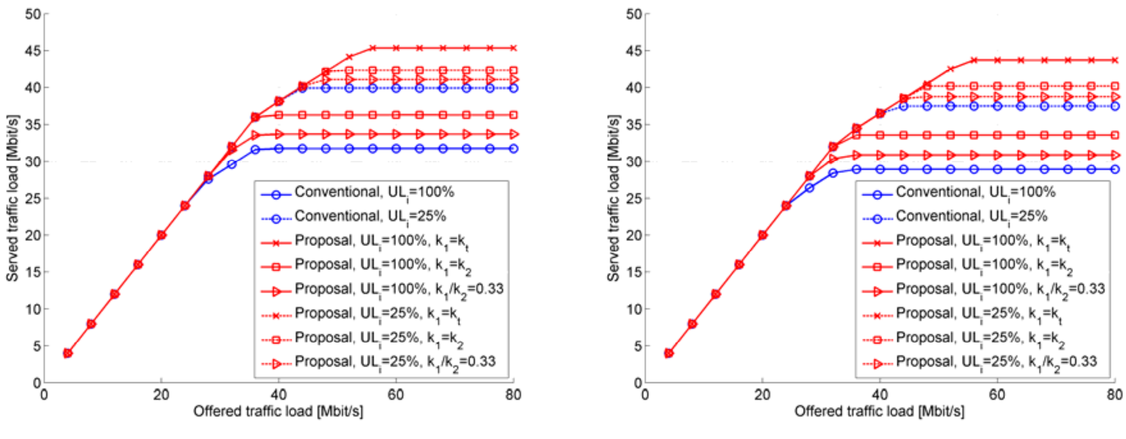


Figure 10. Numerical comparison of both routing schemes in term of throughput; PER=0% (left figure) and PER=10% (right figure)

Packet delay

Besides above mentioned throughput gain, a packet delay is an important aspect of QoS. We analyze only delays for packets transmitted indoor the FAP. Propagation time between stations is neglected since the stations are in close proximity. Hence, a delay of *i-th* packet introduced by one hop transmission can be expressed as follows:

$$t_{1hop}^{i} = t_{q,UE}^{i} \tag{13}$$

where $t_{q,UE}$ is the queuing time at the UE. The queuing time can be represented as a time between arrival of packet at MAC layer and a time when the packet is scheduled to be transmitted. The queuing time is dependent on the size of queue, which is limited by station's memory capacity. In addition, the type of queue has an important effect on queuing time. In case of FIFO (First In First Out) memory, a delay introduced by queue can be formulated as:

$$t_{q}^{i} = t_{f} \times \frac{S}{s_{f}} \tag{14}$$

where t_f is the length of frame duration, S corresponds to the amount of data in station's memory and s_f represents the amount of data sent per one frame. The delay of *i-th* packet for two hop transmission can be characterized as:

$$t_{2hop}^{i} = t_{q,UE}^{i} + t_{p,FAP}^{i} + t_{q,FAP}^{i} \tag{15}$$

where $t_{q,FAP}$ is queuing time at the FAP, and $t_{p,FAP}$ corresponds to a processing time of the packet at the side of the FAP. A processing time is represented by a time necessary to determine whether the packet is received without errors. Consequently, a two hop transmission generally prolongs packet delays by:

$$t_{d} = t_{2hop}^{i} - t_{1hop}^{i} = t_{p,FAP} + t_{q,FAP} \tag{16}$$

The additional factor having impact on packet delay is packet error rate since packets not successfully received have to be retransmitted. To that end, the one hop delay of retransmitted packet can be expressed as:

$$t_{r,1hop}^{i} = t_{q,UE}^{i} + t_{r} \times m_{r,1hop}^{i} \tag{17}$$

where t_r represents a retransmission time and $m_{r,1hop}$ is the number of retransmissions. Similarly, in the case of two hop transmission, delay of retransmitted packet is formulated as:

$$t_{r,2hop}^{i} = t_{q,UE}^{i} + t_{p,FAP}^{i} + t_{q,FAP}^{i} + t_{r} \times m_{r,2hop}^{i} \tag{18}$$

where $m_{r,2hop}$ is the overall amount of retransmissions on both hops. Consequently, the packets transmitted via two hops are more delayed since the probability of retransmission is higher.

To compare our proposed scheme with conventional scheme we consider one transmission session similarly as in the case of throughput gain derivation. During this transmission session, k packets are sent. In the case of conventional scheme, the number of packets sent without (with) errors is denoted as n (n_r). In addition, we denote n_1 ($n_{r,1}$) as a number of packets transmitted directly without (with) errors, and n_2 ($n_{r,2}$) as the number of packets transmitted via two hops without (with) errors (i.e., $k=n+n_r=n_1+n_2+n_{r,1}+n_{r,2}$). Thus, the average UL packet delay achieved by the conventional scheme can be formulated as:

$$t_{avg}^{c} = \frac{1}{k} \times \left(\sum_{i=1}^{n} \left(t_{q,UE}^{i} + t_{p,FAP}^{i} + t_{q,FAP}^{i} \right) + \sum_{i=1}^{n_r} \left(t_{q,UE}^{i} + t_{p,FAP}^{i} + t_{q,FAP}^{i} + t_{r} \times m_{r,2hop}^{i} \right) \right) \tag{19}$$

Similarly, the average packet delay for the proposal scheme can be expressed as:

$$t_{avg}^{p}=\frac{1}{k}\times\left(\sum_{i=1}^{n_1}t_{q,UE}^{i}+\sum_{i=1}^{n_{r,1}}\left(t_{q,UE}^{i}+t_r\times m_{r,1hop}^{i}\right)+\sum_{i=1}^{n_2}\left(t_{q,UE}^{i}+t_{p,FAP}^{i}+t_{q,FAP}^{i}\right)+\sum_{i=1}^{n_{r,2}}\left(t_{q,UE}^{i}+t_{p,FAP}^{i}+t_{q,FAP}^{i}+t_r\times m_{r,2hop}^{i}\right)\right)\quad(20)$$

According to (19) and (20), the average packet delay in the case of the proposed scheme is always lower if $n_2<n$. To satisfy this condition, at least some packets has to be sent directly to the UE (i.e., $n_1>0$).

Figure 11 depicts the numerical comparison of average packet delays achieved by our proposal and the conventional routing scheme. Similarly as in Figure 10, three cases differing in the k_1 (k_2) duration are distinguished. Furthermore, 5 Mbit/s and 10 Mbit/s sent in DL from the FAP to the UEs are considered emulating FAP's background traffic. When the UE is not able to transmit all data in UL, the packets are supposed to be discarded and not included in overall packet delays. On the other hand, if the UL throughput is higher than the DL throughput, data are stored in the FAP's memory, which is limited to 1 Mbit. This value is taken with respect to achieve acceptable UL packet delays. Therefore, if the memory is full, less data in are transmitted in order to avoid further packet losses at the FAP. Figure 11 shows results for both packet error free environment (PER = 0%, left figure) and packet error rate equal to 10% (PER = 10%, right figure).

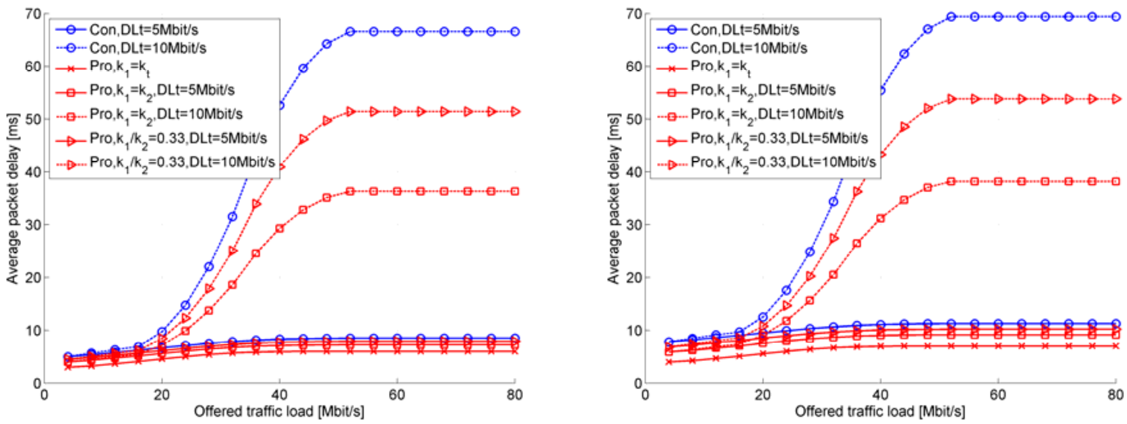


Figure 11. Numerical comparison of both routing schemes in terms of packet delay; PER=0% (left figure) and PER=10% (right figure)

The results indicate that our proposal achieves lower packet delays in all scenarios. The slight increase of packet delays with increase of offered traffic load in the case of our proposal is caused by the fact that the frame is more utilized. Thus, some packets are sent later in the frame, which results in higher delays. If the background traffic in DL is low, the average packet delays observed for conventional scheme are longer only up to 3 ms depending on ratio of k_1 and k_2. In this case, the FAP is able to retransmit all traffic generated by UE in UL to the target UE. Thus, higher delays are only due to FAP's processing time. Nevertheless, higher DL utilization by background traffic increases packet delay significantly. In comparison with our scheme, the users experience approximately up to 30 ms longer packet delays if the conventional scheme is applied. Note that if k_1=k_t, packet delay is not influenced by the amount of background traffic since all packets are transmitted directly in UL. The performance of the proposed scheme is positively affected if amount of packets sent via the FAP decreases. In any case, the proposal outperforms conventional routing always when k_1>0.

The packet delays are prolonged if packets have to be retransmitted (i.e., PER > 0%). For this case, it is demonstrated that the conventional scheme is more susceptible to higher packet error rate than the proposed one (see bottom figure in Figure 20). This is again due to the fact that the probability of packet error increases if data are transmitted two times.

In this section, the performance of both routing schemes is compared analytically. Nevertheless, the performance is significantly affected by several factors such as UEs' movement, interference variations, traffic load fluctuation, etc. The next two sections focus on simulations, which purpose is to investigate the effects of above mentioned factors on the performance of both proposed and conventional routing schemes.

4.1.4 System model

To evaluate the proposed routing scheme by means of simulations, a simulator in MATLAB system is developed. The simulations are done for TDD LTE-A system with DL/UL configuration "1", i.e., four U subframes, four D subframes, and two S subframes are considered. Summarization of basic parameters' setting is indicated in Table 1.

The system model contains one hundred terraced houses with structure according to [Claussen08]. The disposition of the houses is depicted in Figure 12. The FAPs are deployed uniformly in a half of the houses. The outdoor users are moving only within sidewalk's boundaries from the south to the north with speed of 1 m/s along straight trajectories. Their distance from the house is selected randomly with equal distribution in range varying between 1 m and 3 m from the house. The intensity of UEs arrival to the system follows Poisson distribution and it corresponds to approximately 70 passing users per one hour. The only purpose of outdoor users is to emulate interference in UL for the FAP's UEs.

Parameter	Value
Carrier frequency [GHz]	2.0
MBS/FAP channel bandwidth [MHz]	20
Frame duration [ms]	10
MBS transmit power [dBm]	43
Max. FAP transmit power [dBm]	21
Outdoor UE transmitting power [dBm]	15
No. of FAPs	50
Loss of int. wall/ext. wall/window [dB]	5 / 10 / 3
Outdoor path loss model	ITU-RP.1238 model
Indoor path loss mode	COST 231 model
Noise [dBm/Hz]	-174
Physical layer overhead [%]	25
Real-time duration of simulation [s]	20 000

Table 1. System settings

Each house with FAP contains four UEs whose movement within the house is based on [Claussen08] as depicted in Figure 12. The UEs are moving along predefined trajectories between waypoints and points of decision. Since the performance of the proposed routing scheme is especially influenced also by the FAP's location in the house, several positions are selected as shown in Figure 12.

The transmitting power of the FAPs is set according to simple power auto-configuration scheme based on [Claussen08]. In other words, the FAP's transmitting power is adjusted to such value that guarantees full house coverage. The transmitting power of indoor UEs is set to the same value as the FAP's. On the other hand, the transmitting power of outdoor UEs is set to fixed value as depicted in Table 1 since these UEs need to be able to communicate with a MBS in UL at much longer distances.

To emulate the susceptibility of wireless channel to error transmissions due to fading effects or interference, two different packet error rates are considered similarly as in the previous section, that is, PER=0% (serves as reference scenario) and PER=10%. If the packet is received with errors its retransmission is supposed to take 10 ms.

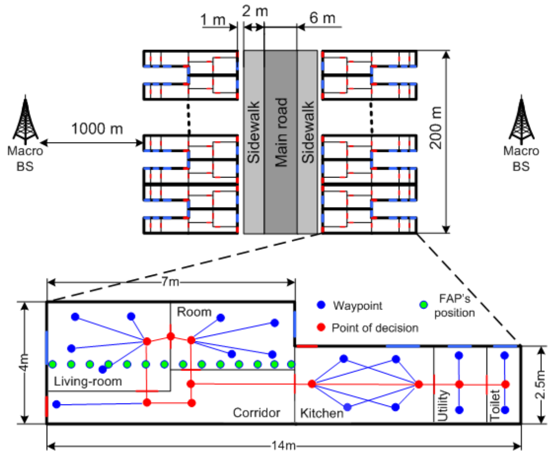


Figure 12. System model and MBSs/FAPs deployment

4.1.5 Results

The performance of the conventional and the proposed schemes is evaluated for constant bit rate (CBR) traffic model and for combination of VoIP and FTP traffic models.

Results for CBR traffic model

The purpose of constant bitrate traffic model is to evaluate the performance of both investigated routing schemes in terms of theoretical maximum throughput achieved by the FAPs. The traffic model generates a specific amount of data in both DL and UL directions per every frame for each UE. The amount of transmitted data depends on the simulation cycle. In the first cycle, the size of generated data corresponds to 10 kbit per user per frame (i.e., CBR generates 8 Mbit/s for all four UEs). Since we assume that only 5 kbits can be sent in one packet, two packets are transmitted in every frame by each station in DL and UL. In subsequent simulation cycles, the amount of data is gradually increased by 10 kbits until 100 kbits (i.e., until CBR generates overall 80 Mbit/s for all four UEs). Note that the packets transmitted in UL directions are always sent to another UE within the same FAP. A destination station is selected randomly according to uniform distribution. In addition, the amount of data generated in every frame remains constant during every simulation cycle (20 000 s).

Figure 13 shows the amount of served traffic load in dependence on offered traffic load. The results are averaged out over all FAPs' positions. If the generated traffic is light, both routing schemes are able to transmit all data. Nevertheless, with increasing traffic load the proposed scheme serves higher amount of data in comparison to the conventional scheme. At heavy traffic load and with error free transmissions, the proposal serves 38.2 Mbit/s while only 31.1 Mbit/s is served in case of the conventional routing. Consequently, the overall throughput gain is up to approximately 22.8%. A performance gap between both routing schemes is further emphasized for PER=10%. In this scenario, the conventional routing scheme serves only up to 28.6 Mbit/s whilst data rates of our proposed scheme are saturated at 36.7 Mbit/s (i.e., observed throughput gain is up to 28.3%). Figure 13 further indicates that results achieved by simulation and analytical evaluations (see Figure 10) are similar. The minor variance in throughput gain is due to different ratio of k_1/k_2 obtained in simulation when compared to analytical results.

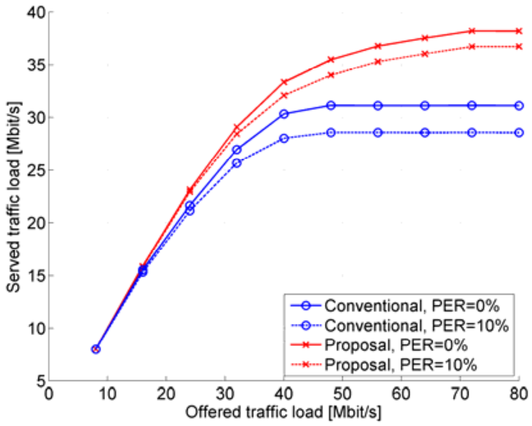


Figure 13. Served traffic load in dependence on offered traffic load

Figure 14 illustrates average throughput for all traffic loads depending on FAPs' position within the building. It is obvious that the performance is not particularly affected in case of the conventional scheme as the throughput is approximately 26 Mbit/s (PER=0%) and 24 Mbit/s (PER=10%). On the other hand, the throughput while utilizing proposed scheme is significantly influenced by the FAP's location. To be more specific, the throughput is highest (32.1 Mbit/s for PER=0% and 31.2 for PER=10%) if the FAP is located close to house boundaries. The throughput gradually decreases if FAP's position is closer to the middle of the building. The reason for this phenomenon is that if the FAP is located at the edge of the house, it is better to utilize direct communication for most of the times as direct route offers better performance. However, if the FAP is located in the middle, direct route is not always feasibly and a probability of two hops transmission increases. Still, disregard on the FAP position, the proposal scheme always outperforms the conventional one as the throughput gain is between 9.3% and 25% (PER=0%) and between 13% and 29.5% (PER=10%).

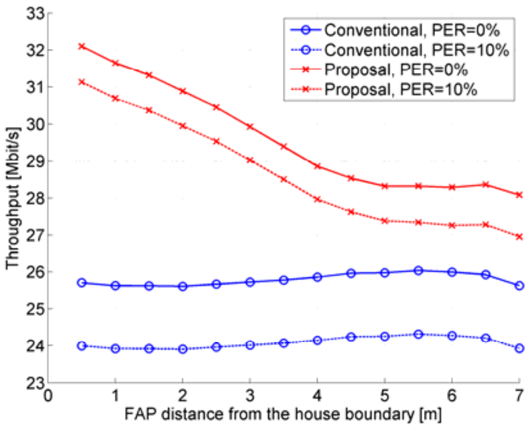


Figure 14. Throughput in dependence on FAP's position

Results for VoIP and FTP traffic models

The second set of simulations evaluates the performance of both schemes for VoIP and FTP traffic models. In this scenario we estimate achieved bit rates when transmitting FTP files between two UEs attached to the same FAP. The model itself generates data files of sizes up to 12.5 Mbytes according to lognormal distribution. The time between two files is on the average 1.7 s, which is given by exponential distribution. To emulate background traffic, that is, data that are not sent between two UEs of the same FAP, a combination of VoIP and FTP models is used. The amount of traffic generated by FTP only is on the average 4.4 Mbit/s.

Figure 15 depicts the performance of routing schemes in terms of average bit rate with which the FTP files are transmitted depending on the FAP's position. Similarly as in Figure 14 the pattern is the same as the bit rates is gradually decreased when the FAP's location is closer to the middle of a building. Nevertheless, the proposal still outperforms the conventional scheme as it guarantees average bitrates varying between 26.7 Mbit/s and 29.3 Mbit/s while the conventional scheme transmits FTP files with bitrates between 24.9 Mbit/s and 26.4 Mbit/s. The observed throughput gain ranges from 7.2% to 10.9%. If the PER increases, the performance of both schemes is partially degraded. However, while the bit rate achieved by proposal is decreased only by 3.2 Mbit/s on the average, the conventional scheme suffers more significantly as the observed bit rate drop is roughly 5.2 Mbit/s. As a result, the proposed scheme outperforms the conventional one up to 23%.

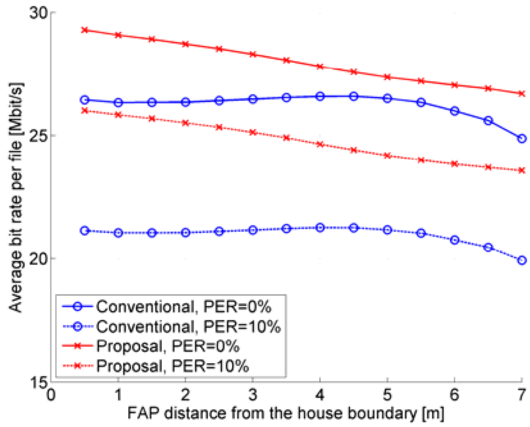


Figure 15. Average bit rate per file generated via FTP model

Figure 16 shows a distribution of bit rates over whole simulation time and over all FAP's position. In case of the conventional routing scheme, 75% of files are sent with transmission speed above 25 Mbit/s if PER=0%. In the case of our proposal, approximately 85% is sent with bitrates above 25 Mbit/s. If PER=10% is assumed, the performance of the conventional scheme is especially negatively influenced as 80% of files are delivered with bitrates lower than 25 Mbit/s. On the contrary, the proposal's performance is not that much degraded since only 35% of generated files are sent with bitrates lower than 25 Mbit/s.

Other performance metric taken into account in the simulations is the packet delays. Since we evaluate the performance of data routing from the UE to another UE within the same FAP, only packets transmitted by the UE which destination station is connected to the same FAP are consider. Thus, the delays of packets originally transmitted by the FAP in DL are not calculated. If current capacity in UL is higher than in DL (e.g., if DL background traffic is transmitted at the same time), the packets are stored in the FAP's memory and transmitted later. The size of the FAP memory is set to 1 Mbit/s. Note that the size of the packets is the same as in previous evaluation. In case that the buffer is full, the FAP allows to transmit in the UL only such amount of data which can be also transmitted in the DL. Thus, it is guaranteed that no data are discarded at the side of the FAP even if some packets transmitted from the FAP to the UE have be retransmitted due to error reception.

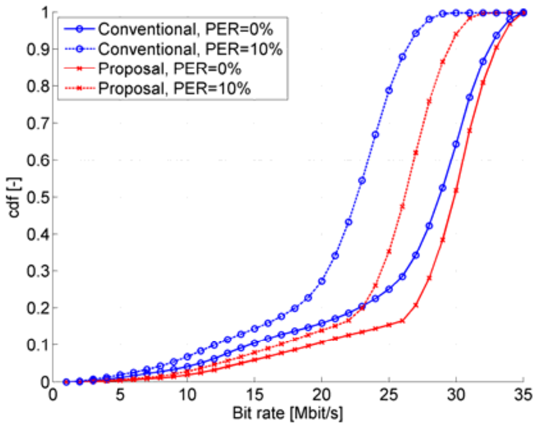


Figure 16. Distribution of bit rates observed for all files generated via FTP model

Figure 17 illustrates average UL packet delays in relation to the FAP's location within the building. The packet delays for conventional scheme remains constant for all FAP's position and correspond to 25.5 ms (PER=0%) and 27.5 ms (PER=10%). The packet delays are notable decreased by our proposal and varies from 6.1 ms to 12.4 ms (PER=0%) and from 7.2 ms to 13.6 ms (PER=10%). The packet delays are increased with FAP's position farther from the building edge due to the same reason as explained previously, i.e., since the direct UEs' communication is not always feasible if the FAP is closer to the middle of the house.

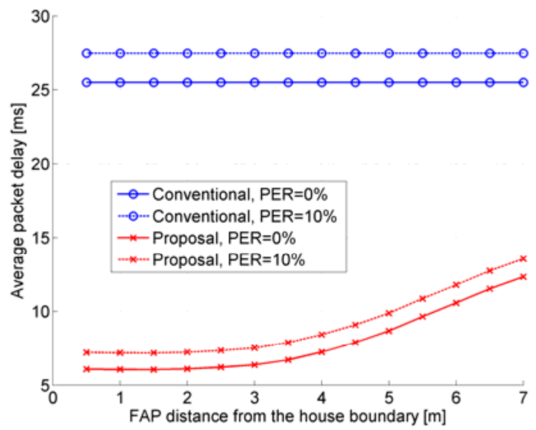


Figure 17. Average UL packet delays of files generated via FTP model

The UL packet delay distribution is depicted in Figure 18. The packet delays are at most equal to 250 ms. Note that this value is mainly limited by FAP's buffer memory as mentioned above. Figure demonstrates that 95% of all packets are delivered within 11 ms (PER=0%) and 19 ms (PER=10%) if our proposal is implemented. On the other hand, the conventional scheme is able to transmit 95% packets within 81 ms (PER=0%) and 83 ms (PER=10%).

4.1.6 Conclusions and discussion

This section proposed novel routing scheme of data transmission for UEs attached to the same FAP. The performance of the proposal was analyzed both analytically and by means of performed simulations. It is demonstrated that our proposal is able to outperform conventional approach both in terms of throughput and packet delay.

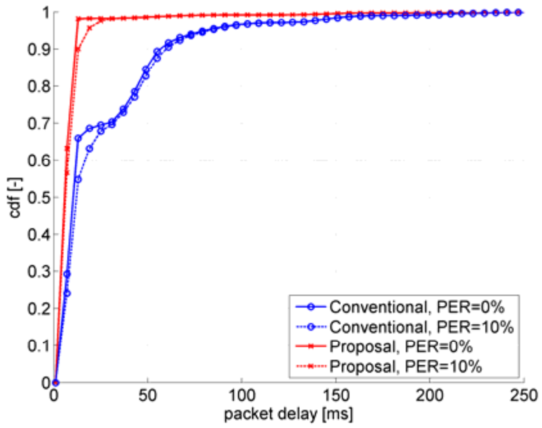


Figure 18. Distribution of UL packet delays

4.2 Fast power control procedure

4.2.1 Introduction

This study focuses on a power control mechanism and proposes a novel approach for dynamic transmitting power adaptation of femtocells. The basic idea is to adapt the transmitting power of femtocells according to the current traffic load and signal quality between UE and the femtocell in order to fully utilize radio resources allocated to the femtocell. The advantage of this approach is its potential to decrease interference to users of macro cell or adjacent femtocells at light traffic load.

4.2.2 Principle of proposed power control mechanism

The general principle of the proposed scheme is depicted in Figure 19. The left part of the figure shows the case when the transmitting power of FAP is adjusted to achieve $CINR_{Target}$ (Carrier to Interference and Noise Ratio) at radius r_1, which could correspond, for example, to the house boundaries. If the channel quality, characterized by the $CINR_1$, at the side of both UEs is distinguishable higher than $CINR_{Target}$ and the radio resources of the FAP are not fully utilized, the FAP's transmitting power is decreased while no negative impact on QoS is observed. The power is adjusted to such value when the received signal from the FAP at the side of both UEs is still acceptable (in Figure 19b depicted as $CINR_2$) and that all data can be still transmitted. The proposed scheme adjusts transmitting power of reference signals (RSs), which purpose is to estimate channel quality, and data. In our proposal we assume that the data in DL direction are transmitted with the same power as RSs. Thus, an opportunistic decrease of transmitting power of RSs helps to minimize the number of mobility events since the handover is initiated according to received quality of RSs [Sesia09].

Actual frame utilization must be known at the side of FAP to estimate current appropriate transmitting power of FAP (P_t). According to [TS36.300_10.0.0] the LTE-A frame is composed of 20 slots with 0.5 ms duration in a time domain. Every two slots create one subframe and ten subframes form one LTE-A frame. Furthermore, one slot includes seven OFDM symbols (or six OFDM symbols if extended cyclic prefix is considered). Depending on channel bandwidth, the frame structure could be decomposed in a frequency domain into certain number of subcarriers and every twelve subcarriers form one resource block. The resource block consists of so called resource elements representing one subcarrier in the frequency domain and one OFDM symbol in the time domain.

For the purpose of our proposed power control scheme, it is necessary to analyze aspects influencing current frame utilization. This issue is addressed in the next subsection.

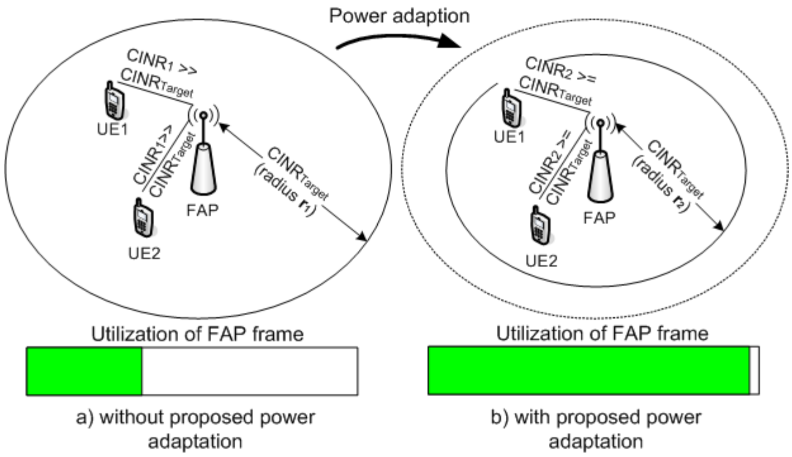


Figure 19. Basic principle of the proposed scheme.

4.2.3 Assessment of parameters influencing frame utilization

The first aspect having an effect on the frame utilization is the amount of resource elements dedicated for data transmission and signalization. In compliance with the previous subsection, the overall number of resource elements in the frame can be expressed as:

$$n_{REpF} = n_{SC} \times n_{SMB} \tag{21}$$

where n_{SC} stands for the number of subcarriers in the frequency domain (depends on selected channel bandwidth) and n_{SMB} represents the amount of OFDM symbols per frame in the time domain. The current frame utilization can be formulated as:

$$\vartheta = \frac{n_{OH} + n_D}{n_{REpF}} \tag{22}$$

where n_{OH} and n_D represent the number of resource elements appointed to control information and data respectively. Thus, as long as $n_{OH} + n_D < n_{REpF}$, the frame is not fully used and some resources are still free. The number of resource elements carrying overhead depends on system configuration and usually varies between 15 % and 30 % of n_{REpF} (see [Abe09]).

The second aspect having an impact on current frame utilization corresponds to the amount of traffic transmitted between the FAP and its users in downlink direction during current frame. This parameter could be expressed as:

$$\Theta = \sum_{j=0}^{n} TL_j \tag{23}$$

where n is the number of users attached to the FAP and TL_j is current amount of data send to j user. In general, the number of resource elements used for data transmission is proportional to the amount of generated data in the downlink direction.

The last aspect influencing current frame utilization is represented by a transmission efficiency Γ. The Γ parameter determines the amount of bits sent via one resource element, i.e., the number of bits sent over one subcarrier in the frequency domain and one OFDM symbol in the time domain. The parameter Γ is dependent on chosen Modulation and Coding Scheme (MCS) assigned according to the received CINR. Here, the MCS is selected in the line with [Yu09] as indicated in Table 2.

The parameter Γ is proportional to the FAP's transmitted power since CINR can be calculated as:

$$CINR = P_t - PL - NI \tag{24}$$

where P_t is the transmitting power of FAP, *PL* corresponds to the signal attenuation between a transmitter and a receiver, and *NI* stands for the noise plus interference.

CINR [dB]	MCS	Transmission efficiency Γ
-1<CINR<=1.5	1/3 QPSK	0.66
1.5<CINR<=3.8	1/2 QPSK	1
3.8<CINR<=5.2	2/3 QPSK	1.33
5.2<CINR<=5.9	3/4 QPSK	1.5
5.9<CINR<=7.0	4/5 QPSK	1.6
7.0<CINR<=10	1/2 16QAM	2
10<CINR<=11.4	2/3 16QAM	2.66
11.4<CINR<=12.3	3/4 16QAM	3
12.3<CINR<=15.6	4/5 16QAM	3.2
15.6<CINR<=17	2/3 64QAM	4
17<CINR<=18	3/4 64QAM	4.5
18<CINR	4/5 64QAM	4.8

Table 2. Transmission efficiency depending on CINR [Yu09]

4.2.4 Impact of FAP's transmitting power on frame utilization

If the transmitting power P_t either increases or decreases, CINR received at the side of UEs is changed as well (see (24)). An increase (decrease) of P_t leads to proportional increase (decrease) of CINR experienced by the UEs (for better understanding of the principle, *PL* and *NI* are considered to be unchanged between two reporting intervals). This could be interpreted as:

$$\begin{aligned} CINR_{(P_{t,new})} &> CINR_{(P_{t,old})} \text{ if } P_{t,new} > P_{t,old} \\ CINR_{(P_{t,new})} &< CINR_{(P_{t,old})} \text{ if } P_{t,new} < P_{t,old} \end{aligned} \tag{25}$$

As a result, the MCS can be switched to the one with higher (lower) transmission efficiency Γ since the channel quality is improved (worsen) as indicated in Table 2. Subsequently, the number of resource elements used for data transmission can be expressed as:

$$n_D^k = \sum_{j=0}^{n} \frac{TL_j^k}{\Gamma_j^k} \tag{26}$$

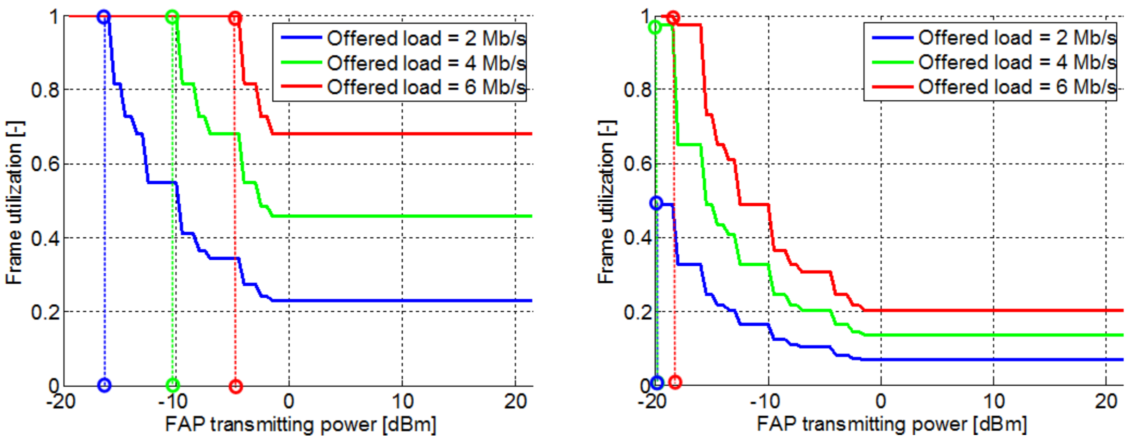
where Γ_j^k is transmission efficiency of user j in frame k. It is clear that higher (lower) transmission efficiency reduces (raises) the amount of resource elements used for data transmission as indicated in following formula:

$$\begin{aligned} n_{D(\Gamma_{j,new}^k)}^k < n_{D(\Gamma_{j,old}^k)}^k \quad \text{if } \Gamma_{j,new}^k > \Gamma_{j,old}^k \\ n_{D(\Gamma_{j,new}^k)}^k > n_{D(\Gamma_{j,old}^k)}^k \quad \text{if } \Gamma_{j,new}^k < \Gamma_{j,old}^k \end{aligned} \tag{27}$$

Finally, if the number of resource elements assigned for data transmission n_D^k is reduced (raised), the frame utilization is also decreased (increased) as could be seen from (22) and expressed as:

$$\begin{aligned} \vartheta_{(n_{D,new}^k)} < \vartheta_{(n_{D,old}^k)} \quad \text{if } n_{D,new}^k < n_{D,old}^k \\ \vartheta_{(n_{D,new}^k)} > \vartheta_{(n_{D,old}^k)} \quad \text{if } n_{D,new}^k > n_{D,old}^k \end{aligned} \tag{28}$$

Thus the proposed power mechanism tries to achieve certain target frame utilization $\vartheta_{\text{target}}$ by changing of FAP's transmitting power in dependence on current traffic load and channel quality between the FAP and UEs.



a) BW = 3 MHz **b) BW = 10 MHz**

Figure 20. Dependence of frame utilization on transmitting power of FAP

Figure 20 shows the example how the frame utilization is influenced by FAP's transmitting power. The frame utilization is calculated for one active UE positioned 2 m from the FAP without any obstacles between the transmitter and receiver. Furthermore, two bandwidth sizes allocated to the FAP are considered while three different traffic loads are generated in DL direction. It is illustrated that with increasing of FAP's transmitting power the frame utilization is decreasing. In general, the higher frame utilization is observed if the offered traffic load is higher and narrower channel bandwidth is used for the same transmitting powers. From Figure 20 could be further derived optimal levels of power allocated to the FAP when the frame utilization is either equal to 1 or lesser. The reason for constant frame utilization for FAP's power levels between -2 and 21 dBm is that the highest MCS is used. Thus the amount of radio resources allocated for data transmission is still the same.

4.2.5 Impact of FAP's transmitting power on mobility events

In general, mobility event is generated if the UE initiates handover procedure. The mobility event occurs if the UE moves from the MBS to FAP or vice versa and when the UE crosses between two adjacent FAPs. Thus UE moving close to the FAP positioned in the building may perform handover to this FAP and within moment switches back to the MBS, i.e., two mobility events are generated. Consequently, the objective of the power control is to avoid handovers from the MBS to FAP in the first place. The handover is always performed if:

$$s_t(t) > s_s(t) + \Delta_{HM}\ ,\ t \in \left(t, t + HDT\right) \tag{29}$$

where $s_t(t)$ and $s_s(t)$ are pilot's signal levels received from a target station (station to which the UE is supposed to be connected after handover) and a serving station (station to which the UE is attached before handover) respectively, and Δ_{HM} represents hysteresis margin for avoiding redundant handovers. Furthermore, in order to prevent any other unnecessary handovers, its initiation is postponed by handover delay timer *HDT*.

To identify the relation between transmitting power and amount of initiated handovers, we can express signals $s_s(t)$ and $s_t(t)$ as follows:

$$\begin{aligned} s_s(t) &= P_{t,s} - PL_s(t) - u_s(t) \\ s_t(t) &= P_{t,t} - PL_t(t) - u_t(t) \end{aligned} \tag{30}$$

where $P_{t,s}/P_{t,t}$ represents pilot's transmitting power of BS/FAP, $PL_s(t)/PL_t(t)$ corresponds to the path loss between MBS/FAP and UE, and $u_s(t)/u_t(t)$ stands for shadowing function. By combination of (29) and (30), handover from the MBS to FAP is initiated if:

$$P_{t,t} - PL_t(t) - u_t(t) > P_{t,s} - PL_s(t) - u_s(t) + \Delta_{HM}\ ,\ t \in \left(t, t + HDT\right) \tag{31}$$

If we consider handover from the MBS to FAP, i.e., $P_{t,s}$ is the transmitting power of the MBS and $P_{t,t}$ corresponds to transmitting power of FAP, it is apparent that a probability of handover decreases with lowering of FAP's transmitting power. Since the goal of the proposed power control is to fully utilize the frame by decreasing of FAP's transmitting power, the overall number of performed handovers may be potentially minimized.

4.2.6 Analytical evaluation of the proposed scheme

The aim of this section is to evaluate the proposed scheme analytically. In other words, the objective is to investigate how the position of UEs within the house and their signal quality received from the FAP has impact on FAP's transmitting power.

4.2.6.1 Assumptions

To study analytically the performance of the proposed power control scheme, we are considering parameters depicted in Table 3. For the purpose of analytical evaluations the structure of house according to [Claussen08a] is considered (see Figure 21). The analyses take into account two different positions of FAP. While the first position (in Figure 21 depicted as FAP_pos1) corresponds to the same location as assumed in above mentioned proposals [Claussen08a][Claussen08b][Choi09], the second position is intentionally chosen at the house edge (in Figure 21 depicted as FAP_pos2), i.e., the case representing the worst case scenario as the interference is the most significant. The evaluation process is done in such manner that always one position of UE is randomly selected. After that the transmitting power of FAP is set to a level, which guarantees the highest frame utilization. This process is repeated one thousand times and the final results are averaged out.

To simulate path loss in indoor environment, ITU-RP.1238 model is implemented (for detail see e.g. [Femto10]). For the sake of simplicity, the interference level from the MBS (which is dominant in our scenario) to the FAP is either of high level (equal to -75 dBm) or of low level (equal to -95 dBm). Thus, the former case corresponds to the scenario when the FAP is in close vicinity of MBS while the latter case represents the scenario when the FAP is relatively in large distance from the MBS. Nevertheless, this simplification does not affect the analytical results. To cope with fading effects, fade margin of 4 dB is assumed.

Parameter	Value
Frequency band [GHz]	2.0
Channel bandwidth [MHz]	3;5;10
Frame duration [ms]	10
Number of OFDM symbols per slot [-]	7
Max. FAP transmit power P_{tmax} [dBm]	21
Noise+interference at the edge of house [dBm]	-75;-95
$CINR_{min}$ [dB]	-1
Target frame utilization ϑ [-]	1
Generated traffic load [kb]	100-10000
Loss of internal wall/external wall/window [dB]	5/10/3
Fade margin [dB]	4
n_{PDCCH}	1

Table 3. System settings

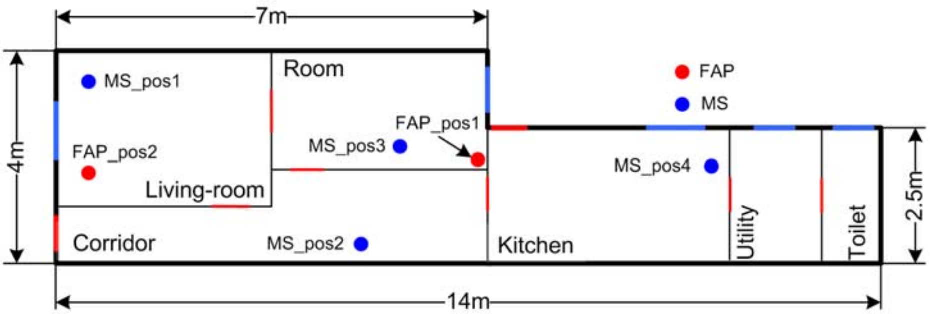
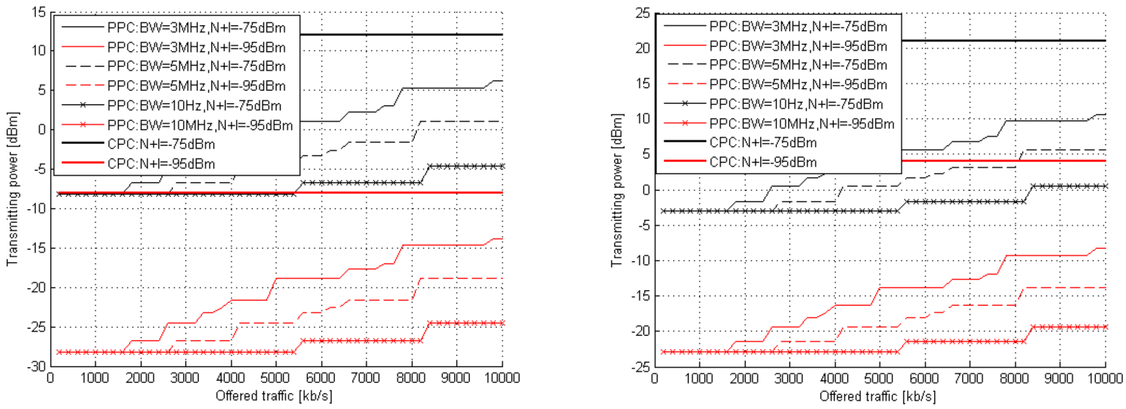


Figure 21. House structure [Claussen08a]

The performance of proposed scheme (in the next Section labeled as PPC - Proposed Power Control) is compared to the already proposed schemes when the aim is to cover by FAP area of certain radius (in the next Section labeled as CPC - Conventional Power Control).

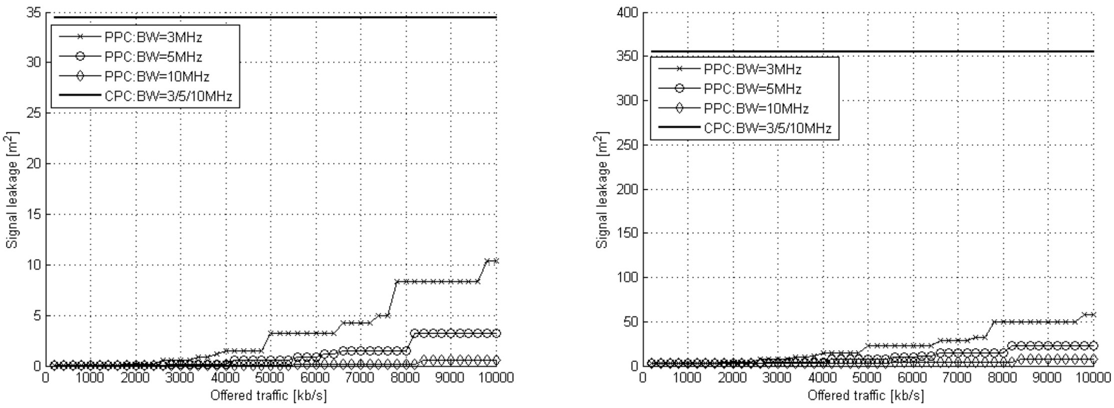
4.2.6.2 Analytical evaluations results

Figure 22 demonstrates how the transmitting power of FAP is influenced if different channel bandwidth is considered together with varying noise plus interference ratio. From figures it is apparent that more significant reduction of transmitted power can be achieved for the wider channel. This is due to the fact that generally with wider channel more radio resources are available. Thus, we can decrease transmitting power more significantly and still be able to transmit all data within one frame. To be more specific when the system channel bandwidth is set to 10 MHz instead of 3 MHz, we can decrease the transmitting power up to 12 dB more for the former case. Consequently, the advantage of PPC is more obvious in comparison with CPC schemes. Additionally, Figure 22 illustrates that transmitting power is increased proportionally with increase of noise plus interference ratio as well.



a) FAP located in the middle of house **b) FAP located at the edge of house**

Figure 22. Transmitting power of FAP depending on offered traffic load



a) FAP located in the middle of house **b) FAP located at the edge of house**

Figure 23. Signal leakage depending on offered traffic load

Figure 23 analyses the amount of FAP's signal leakage out of house in dependence on traffic load. By leakage of the signal is meant the area out of house where the signal from the FAP is stronger than the signal from the MBS. In case when the FAP is located in the middle of the house, the leakage of the signal is negligible. For CPC scheme the leakage is approximately 35 m^2 while for PPC scheme only up to 10 m^2. On the other hand, if the FAP is positioned at the edge of the house (see Figure 21), the signal leakage is much more profound. Especially for CPC scheme, extensive interference can be induced to users attached to MBS or to adjacent FAPs. More than that, it could cause initiation of unnecessary handovers of moving MS. In this scenario the utilization of PPC scheme largely reduces harmful interference as the leakage of the signal could be mitigated. Even at heavy traffic load (10 000 kb/s) and for narrow channel bandwidth (3 MHz), signal leakage is roughly four times smaller than in case of CPC.

4.2.6.3 Conclusion

The analytical evaluations demonstrated that by means of proposed scheme significant reduction of transmitting power could be achieved when compared to the existing power control schemes. Consequently, leakage of the FAP's signal out of the house is dramatically mitigated. The proposed scheme proves its effectiveness especially for the scenarios when the FAP is located near of the house's edge.

Great potential of proposed mechanism can be seen from the performed evaluation. Nevertheless, it is necessary to investigate its performance also under more realistic conditions (e.g., to implement indoor mobility model for users, to implement traffic models, etc.). Consequently, the next section proposes a power control algorithm, which allows adapting transmitting power as suggested and presents evaluation by means of system level simulation.

4.2.7 Power adaptation algorithm

Table 4 summarizes a notation used in the description of the proposed algorithm. The dynamic adaptation of transmitting power is done every adaptation interval Δt. Firstly, the current frame utilization in the downlink direction is estimated. Whether the transmitting power of FAP is increased, decreased or remains the same depends on several parameters: current frame utilization ϑ, average CINR between individual FAP and its UEs, and current transmitting power of the FAP P_t. Depending on traffic load Θ^k in frame k representing UEs activity and the current frame utilization ϑ, three cases may occur: Case I ($\Theta^k = 0$ and $\vartheta < \vartheta_{\text{target}}$), Case II ($\Theta^k > 0$ and $\vartheta < \vartheta_{\text{target}}$), and Case III ($\Theta^k > 0$, $\vartheta_{\text{target}} \leq \vartheta < 1$ or $\vartheta = 1$ while not all data are sent from the FAP to UEs due to congestion). The target frame utilization $\vartheta_{\text{target}}$ represents a value, which the algorithm aims to reach. In general, the $\vartheta_{\text{target}}$ can take the values between 0 and 1. The value of $\vartheta_{\text{target}}$ is by default set to 1 as the objective is to fully utilize the frame (note the this study also evaluates performance of proposed scheme for lower values of $\vartheta_{\text{target}}$).

Symbol	Semantics
P_t	Transmitting power of the FAP
ΔP	Power adaptation step
P_{min}	Minimal transmitting power of the FAP
P_{max}	Maximal transmitting power of the FAP
$CINR_{min}$	Minimal CINR when the UE is still able to connect to the FAP
$CINR_{max}$	CINR when the data between the FAP and the UE are sent with the highest MCS
ϑ	Current frame utilization
$\vartheta_{\text{target}}$	Target frame utilization
X^m	The set of UEs' average CINR of the FAP m, $\mathrm{X}^m = [\chi_1^m, \chi_2^m, ..., \chi_n^m]$
Δt	Power adaptation interval
FM	Fade margin to cope with fading effects

Table 4. Notations

The Case I occurs when all UEs connected to the FAP are in inactive state ($\Theta^k = 0$). In order to minimize potential interference to passerby users, the transmitting power of the FAP is automatically set to its minimal value P_{min}. To prevent the handover of UEs in idle state to other station with higher transmitting power (either to MBS or to adjacent FAPs), the handover threshold is decreased accordingly.

The Case II corresponds to the situation when $\vartheta < \vartheta_{\text{target}}$ while some of the UEs are active ($\Theta^k > 0$). As Figure 24 indicates, the transmitting power of FAP can be either increased or decreased. The power has to be increased if at least one UE attached to the FAP is receiving weak signal (i.e., $\exists \chi^m \in X^m < CINR_{\min} + FM$) to avoid possible termination of data transmission by this UE. The fading margin FM guarantees that the UE is not disconnected due to fading effects. In addition, the power of FAP is incremented by power adaptation step only if the new value would not exceed P_{max}.

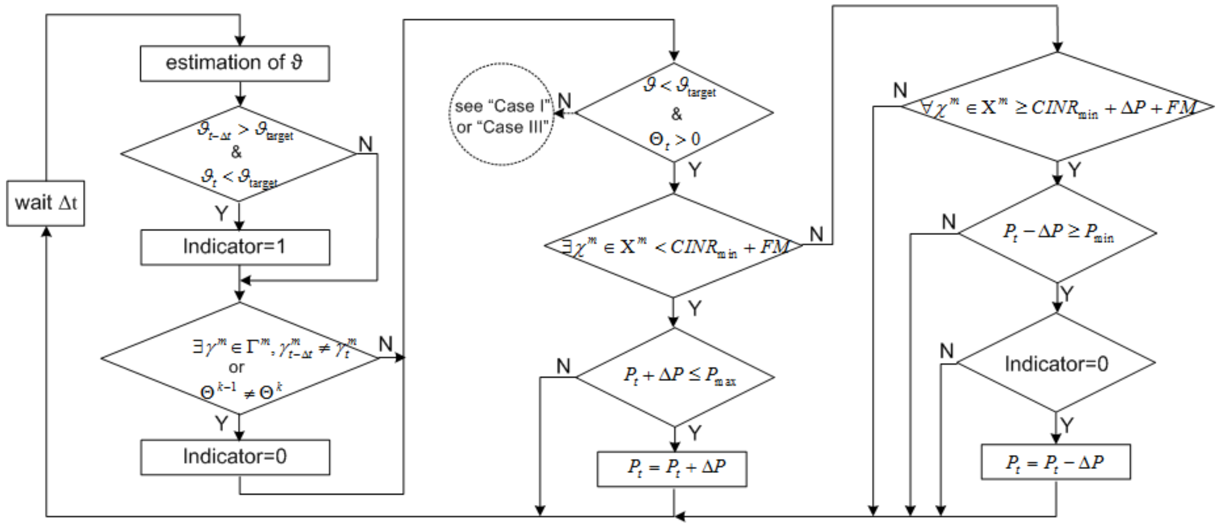


Figure 24. The principle of power adaptation algorithm for Case II

On the other hand, the power is decreased if all UEs connected to the FAP are receiving signal with satisfying quality (i.e., $\forall \chi^m \in X^m \geq CINR_{\min} + \Delta P + FM$). The decrease of transmitting power is profitable since the interference is minimized. Nevertheless, two more requirements need to be satisfied to lower FAP's transmitting power. The first one is fulfilled if the new transmitting power would be still above the minimal allowed value P_{min}. The purpose of the second one is to avoid continuous adjustment of transmitting power when frame utilization is equal approximately to ϑ_{target} . If this problem would be neglected, the transmitting power could oscillate between two values as indicated in Figure 25a. The oscillation is caused by the fact that as soon as $\vartheta > \vartheta_{target}$, the algorithm increases FAP's transmitting power (see description of Case III below). Nonetheless, in the next adaptation cycle, the FAP's transmitting power would be again decreased (i.e., Case II would be applied). To this end, the algorithm is enhanced by the following mechanism. If the frame utilization in previous adaptation cycle is above ϑ_{target} while in the current cycle it is not (i.e., $\vartheta_{t-\Delta t} > \vartheta_{target}$ and $\vartheta_t < \vartheta_{target}$), the indicator is set to "1" (see Figure 24 and Figure 25b). The algorithm reaches the equilibrium since the transmitting power of FAP is optimal as the frame utilization is closest to the ϑ_{target} as possible. The equilibrium state lasts as long as ϑ remains the same. In other words, the MCS used by all UEs is unchanged (i.e., $\forall \gamma^m \in \Gamma^m, \gamma^m_{t=\Delta t} = \gamma^m_t$) and the amount of data generated in downlink is still the same ($\Theta^{k-1} = \Theta^k$). Otherwise, the indicator value is reset to "0" and new transmitting power achieving the equilibrium is found.

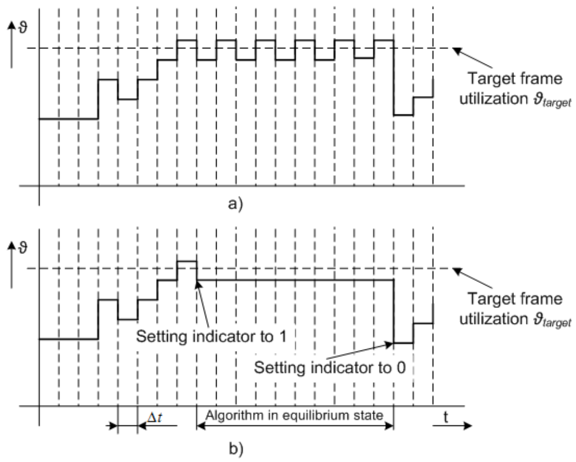


Figure 25. Avoidance of FAP's transmitting power oscillation

The last case (Case III) represents the situation when the FAP's current frame utilization is above target frame utilization (i.e., $\vartheta_{\text{target}} \le \vartheta < 1$) or when $\vartheta = 1$ and the FAP is at the same time overloaded. The transmitting power of FAP is either set directly to P_{max} or increased by ΔP (see Figure 26). The FAP's power is set to its maximal level only when it is overloaded. The reason for immediate rise of the FAP's power to P_{max} is to ensure that data transmissions are not necessarily delayed by proposed mechanism as in case of gradual increase of the FAP's power would be. Nevertheless, the power is set to P_{max} only if at least one of the UEs attached to the FAP experiences channel quality in downlink below $CINR_{max}$. If this is not the case ($\forall \chi^m \in \mathrm{X}^m \ge CINR_{\max}$), the increase of power would be pointless as already all UEs connected to the FAP use the best MCS. Hence, the frame utilization would not be lowered despite the increased transmitting power.

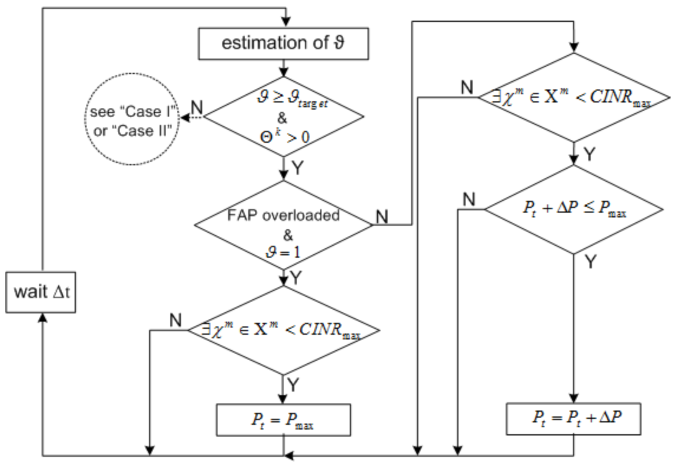


Figure 26. The principle of power adaptation algorithm for Case III

The FAP's power is incremented only by ΔP when $\vartheta_{\text{target}} \le \vartheta < 1$. In this situation, the generated data can be still transmitted and adjusting of the FAP's power by ΔP is sufficient. Before increase of the FAP transmitting power is accomplished, two conditions must be satisfied. The first condition is the same in the previous case, i.e., $\exists \chi^m \in \mathrm{X}^m < CINR_{\max}$. The second condition is that the FAP's transmitting power incremented by a power adaptation step does not exceed maximal allowed value P_{max}.

So far we have assumed the power adaptation is done in such manner that all UEs attached to the FAP would experience satisfying signal quality regardless of their activity/inactivity. Nevertheless, if for example, only one UE in close distance to FAP is active while the rest of attached UEs are inactive, it is profitable to adapt transmitting power to guarantee good channel quality only between the active UE and the FAP. In case when inactive UE changes its status to active, the FAP can automatically increase transmitting power to cover this newly active UE.

The important aspect of the proposed power control algorithm is to achieve fast power adaptation. In order to speed up the whole adaptation process, the proposed algorithm needs to be optimized. The speed of adaptation process have a great impact on the number of mobility events, i.e., on the amount of generated overhead due to the handover process. In particular it is necessary to quickly decrease the transmitting power if the FAP increases power to the maximum value as described earlier. Generally, two parameters influencing speed of adaptation process can be taken into consideration; adaptation interval Δt and power adaptation step ΔP. As the length of the frame in LTE-A is set to 10 ms, it is convenient to set adaptation interval to constant value of 10 ms as well (LTE-A allows to schedule reporting period to 2 ms at most). By this way, the FAP is able to adjust the power after each transmitted frame. Thus, the purpose of optimization process is to find such value of ΔP ensuring the minimal number of mobility events. In other words, if we denote $f(\Delta P)$ as an objective function of the number of generated mobility events, the whole optimization process can be formulated as:

$$\Delta P = \arg\min_{\Delta P} f\left(\Delta P\right) \qquad (32)$$

The optimal value of ΔP is found experimentally by means of performed simulations addressed in the Section "Simulation results". In the proposed algorithm, it is assumed that the adaptation step has constant size. However, the adaptive size of ΔP can be utilized for our purposes.

4.2.8 Requirements imposed by proposed algorithm

The advantage of our proposed power control mechanism is that it needs no additional hardware modifications to the MBS, FAP, or UE. The only requirement is that the FAP is capable to adjust its transmitting power by optimized adaptation step ΔP. Nevertheless, this functionality is required by all existing power schemes. Regarding software changes, the FAP's firmware needs to be updated to support proposed power adaptation algorithm. The algorithm computational complexity is low since no difficult calculations are done, only several simple conditions are evaluated during every power adaptation cycle Δt. As a consequence, the FAP has to collect information regarding the channel quality of all its users in DL every adaptation cycle Δt as well. Since in LTE, a periodic CINR measurement and its reporting can be scheduled from 2 ms to 160 ms [Sesia09], we consider values of Δt varying between 10 ms to 80 ms. Thus the proposal does not unnecessarily increase reporting overhead or FAP's processing load.

In order to implement the proposed algorithm to femtocell environments, two requirements need to be fulfilled: i) the FAP has to be aware of UEs' individual CINR and ii) the FAP has to able to evaluate current frame utilization in downlink direction. As mentioned earlier, the measurement of channel quality and its reporting to the FAP is inherent procedure necessary for all wireless mobile technologies. Consequently, the FAP can adjust the transmitting power as described in previous subsection. In addition, the other advantage of the proposed mechanism is that it does not increase the signaling overhead due to reporting of CINR as the reporting has to be done independently on the proposed power scheme. The second requirement is also satisfied since the FAP is continuously aware of downlink traffic and allocates radio resources to UEs. Thus, the FAP is able to easily determine current frame utilization essential for proposed power adaptation scheme.

4.2.9 Evaluation of the proposed power algorithm

4.2.9.1 System model

If not stated differently, the parameters' setting and simulation scenario is the same as described in section 4.1.4. Modified parameters setting better suited for power control and our proposal are given in Table 5. The simulations are done for FDD LTE-A system. The amount of overhead in the frame is derived from [TS36.300_10.0.0][Abe09] for configuration with one transmitting antenna and varies between 25.8 % and 27.6 % depending on the selected bandwidth.

The system model contains one hundred terraced houses with structure according to [Claussen08a]. Every second house is equipped with one FAP. A disposition of individual houses and MBSs is illustrated in Figure 12. The considered scenario is selected intentionally since it is very challenging as the households are in close proximity of a sidewalk and windows face the sidewalk. Hence, significant amount of undesired mobility events may occur. For more details see section 4.1.4.

Parameter	Value
Channel bandwidth BW [MHz]	3; 5; 10
Number of OFDM symbols per slot [-]	7
Max. FAP transmit power P_{max} [dBm]	21
Min. FAP transmit power P_{main} [dBm]	-20
MBS transmit power [dBm]	43
Noise [dBm/Hz]	-174
$CINR_{min}$ [dB]	-1
$CINR_{max}$ [dB]	18
Target frame utilization ϑ_{target} [-]	1
Fade margin [dB]	4

Table 5. System settings

Since the performance of proposed mechanism strongly depends on the amount of generated traffic by indoor users, two traffic model types based on [IEEE802.16m_EM08] are defined. First traffic model type is a FTP model representing data transmission scenario. More than that, two types of the FTP model are considered (denoted in simulation as a FTP I and a FTP II). While the FTP I generates roughly 380 kb/s at an average per the simulation (corresponding to the light traffic case), the FTP II generates roughly 4.4 Mb/s at an average (corresponding to the heavy traffic case). The second type of model is a VoIP model representing voice transmission.

The performance of the proposed mechanism is demonstrated through the number of mobility events generated per whole simulation depending on the position of the FAP within the household. The mobility event is triggered if the received signal from new cell is higher by 4 dB than serving cell for a time of 500 ms (the values are taken from [Claussen08]). The simulation monitors both outdoor and indoor mobility events. In addition, the level of transmitting power of individual scenario is analyzed.

4.2.9.2 Results

Figure 27 compares the performance of several scenarios in terms of the number of mobility events. The scenario denoted in all following figures as "ACS-MB" represents auto-configuration scheme based on measurement of the mobility events proposed in [Claussen08]. This scenario serves as a benchmark since the observed number of mobility events are normalized to its maximal value at FAP's distance of 0.5 m from the house boundaries. The scenario labeled as "eACS-MB" enhances simple ACS-MB as explained in [Claussen08]. However, in case of FAP's inactivity, the power is decreased to P_{min} (not by 10 dB as describe in [Claussen08]) for fairly comparison with our proposed scheme. Note that eACS-MB represents the best performing power control scheme based on the first approach. The next considered scenario labeled as "SOS" corresponds to self-optimization scheme proposed in [Claussen08] minimizing the number of mobility events at the cost of worse FAP's indoor coverage (based on the second approach). The Figure 27 illustrates the number of all generated mobility events, i.e., both indoor and outdoor mobility events. The performance of proposed scheme is expressed by scenario depicted as "PS I" and "PS II". In the former case the algorithm guarantees that all UEs in the house receive signal from the FAP with satisfying quality regardless on their activity/inactivity. The latter case represents the situation when the FAP adjusts its transmitting power to serve only currently active users.

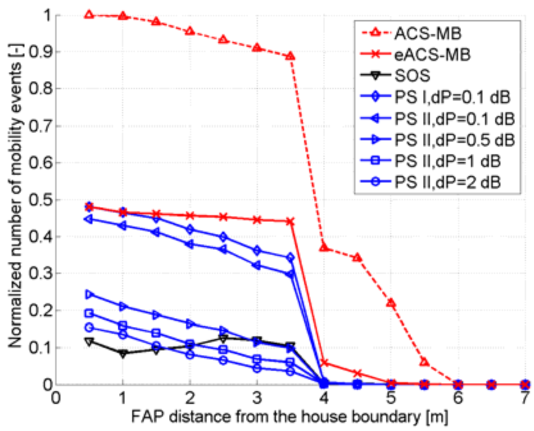


Figure 27. Normalized number of mobility events depending on FAP's position, FTP I, BW=3 MHz

The worst performance is observed by ACS-MB where significant number of the mobility events is generated. Especially if the FAP is close to the house border, the passersby UEs are forced to perform the handover from the MBS or adjacent FAP very often. Although the situation is improved by eACS-MB, which reduces the number of mobility events approximately to 50 %, the results are still unsatisfactory. The overall number of mobility events decreases as the FAP is placed closer to the house centre. The sharp drop of the mobility events between 3.5 m and 4 m is due to two reasons. The first reason is that the FAP is removed from living-room to the next room (see Figure 12). Thus the FAP's power leakage out of house is reduced by attenuation of internal wall. The second reason is that the FAP is transmitting at such power level to cover whole house and the most problematic locality in our scenario is to cover a toilet positioned furthest from the FAP. Thus, when the FAP is moved from living-room to the next room, the power of the FAP is reduced approximately by 5 dB.

The situation is substantially improved by SOS. The number of mobility events is reduced approximately ten times (when compare to ACS-MB) and five times (in comparison to eACS-MB) for FAP's distances between 0.5m to 3.5m from the house boundary. The mobility events are practically eliminated for FAP's distance higher than 3.5m. Nonetheless, drawback of this mechanism is that UEs within the house boundary are not always connected directly to the FAP since the signals from other stations (especially from the MBS) are stronger. In the performed simulation the UE is served by the FAP on average only by 47 % of simulation time if FAP's position is close to the house boundary (see Table 4). Even though the results are improved for farther FAP's locations, the PS and both ACS methods always assure 100 % FAP's coverage within the household. Thus, the main purpose of the FAP, i.e., to cover whole house is not fully accomplished as in case of ACS-MB and PS schemes. More than that, the indoor mobility increases the overall number of mobility events occurred during simulation (this is notable in Figure 27 for the FAP's position between 1.5 m and 3.5 m).

The performance of the proposed mechanism is dependent on the selection of the appropriate adaptation step *ΔP*. If the adaptation step is set to the default value of 0.1 dB and PS I is considered, the number of mobility events is decreased roughly to 50% when compare to ACS-MB. The obtained results are only slightly better than in case of eACS-MB. Further minor improvement is achieved by utilizing of PS II. In order to improve the results obtained by PS, the optimal value for adaptation power step *ΔP* is necessary to be found as described in section 4.2.7. The performance of PS II is also illustrated in Figure 27 for different values of ΔP. The results indicate that the number of mobility events is noticeably decreased if appropriate value for *ΔP* corresponding to 2 dB is selected (no improvement for *ΔP* values higher than 2 dB was observed in simulations). The important outcome is that due to optimization process, the results are even better than in case of SOS for FAP's position greater than 2m from the house's edge.

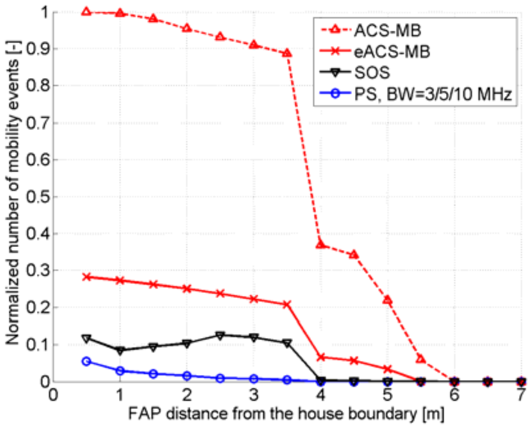
FAP's position [m]		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
FAP's coverage [%]	**SOS**	47	50	52	53	63	71	86	100	100	100	100	100	100	100
	PS, ACS	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 6. Perceptual coverage of UEs by the FAP

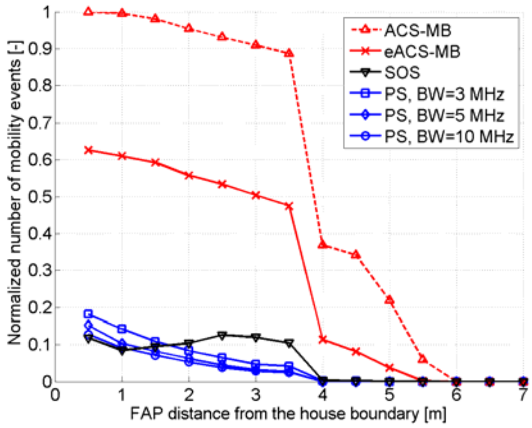
The other parameters that can potentially influence the efficiency of the proposal are: i) amount of generated traffic (in Figure 27, FTP I was used), ii) FAP's bandwidth (in Figure 27, BW = 3 MHz was utilized), and iii) the length of adaptation interval *Δt (*in Figure 27, *Δt* = 10 ms was considered). Note that the number of mobility events observed in case of ACS and SOS is independent on these parameters and eACS performance is influenced only by traffic type (inactivity and activity periods). Consequently, the impact of above mentioned parameters is investigated only on PS. In addition, from now on only PS II utilizing optimal *ΔP* will be considered. Figure 28a takes into account simple VoIP model without any data transmission. This case corresponds to the scenario when users utilize the FAP only to handle voice calls.

The proposed mechanism always outperforms all schemes independently on the selected channel bandwidth. Figure 28b further indicates that if the FAP transmits voice together with data (FTP I + VoIP), the results are rather in favour of PS than of SOS if the FAP is positioned in sufficient distance from the house boundary (at least 1.5 m for BW = 5/10 MHz and at least 2 m for BW = 3 MHz). The performance of eACS-MB has been significantly degraded (in comparison with VoIP model) due to higher UEs activity. If the FTP II together with VoIP is used instead of FTP I, the performance of PS and eACS-MB is distinguishable worse (see Figure 28c). Nevertheless, the number of mobility events for PS is significantly lowered for wider channel bandwidth despite of high traffic load generated by FTP II and VoIP models. In fact, the PS is still able to outperform SOS scheme if at least bandwidth of 10 MHz is allocated to the FAP and when reasonable FAP's position inside the household is selected (at least 2 m from the house boundary). Figure 28c further illustrates the influence of varying *Δt* on PS scheme (note that in case of VoIP and FTPI + VoIP traffic models no negative effect on PS's performance was found). It is demonstrated that for longer adaptation intervals the number of mobility events is increased. Nevertheless, in case of 10 MHz channel bandwidth the negative effect is insignificant as the PS still performs better for FAP's located at least 2.5m from house edge.

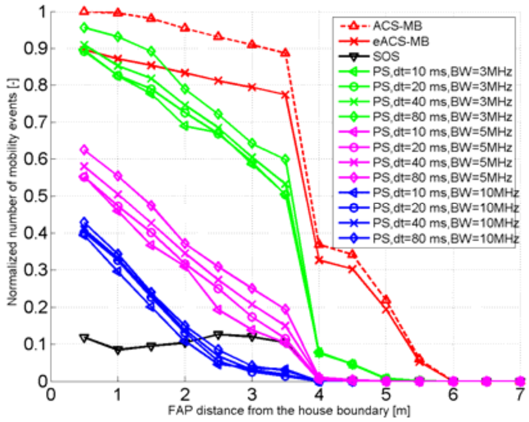
Figure 29 depicts the performance of individual schemes in terms of achieved throughput for selected traffic models and channel bandwidth allocated to the FAP. For better comparison of schemes and scenarios, the throughput is normalized to maximal value obtained during the evaluation. Furthermore, performance is analyzed only for 10 MHz bandwidth in case of low traffic load (VoIP, FTPI + VoIP) since the results for other bandwidths are similar. The scenarios labeled as "Indoor" corresponds to the average throughput reached by one FAP. The aim is to achieve the same indoor throughput as in case of ACS-MB scheme for individual schemes. The reason is that ACS-MB is transmitting with highest power and provides the best house coverage. On the other hand, the scenarios marked as "Overall" represent the throughput obtained by the FAP and MBS together. Consequently, these scenarios show the negative effect of FAP on passersby users attached to the MBS since higher FAP's transmitting power lowers the CINR experienced by passerby UEs.



a) VoIP



b) FTP I + VoIP

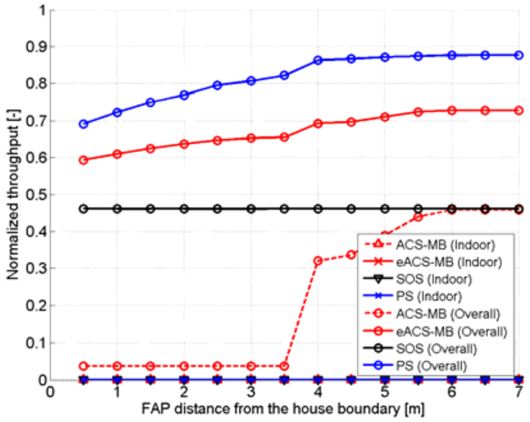


c) FTP II + VoIP

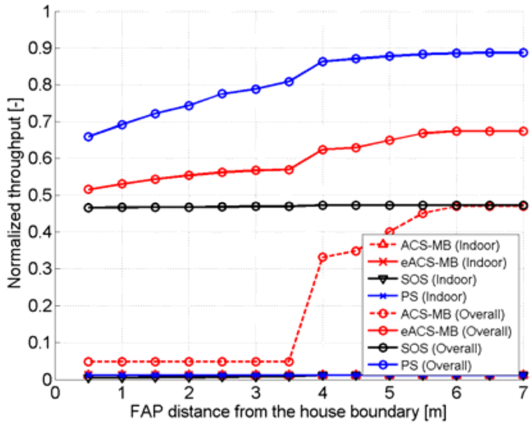
Figure 28. Impact of traffic type and bandwidth size on the number of generated mobility events

If the PS scheme is used the FAP is always able to serve the same amount of data as in case of ACS-MB or eACS-MB. This is not valid for SOS method as indoor users are not attached to the FAP all the time. Consequently, the MBS has to serve these users which degrade the overall throughput. This is notable especially for heavy traffic load when FTPII together with VoIP is used for indoor users. Figure 29 further indicates that simple ACS-MB significantly degrades performance of outdoor users. Nevertheless, if the FAP is close to the middle of house (FAP distance from the house boundary is at least 6 m in our scenario), the results are comparable to SOS scheme as the FAP transmitting power is the same for both methods. Significantly better results than those reached by ACS-MB are observed for eACS-MB when the results are even better than for SOS scheme. Nonetheless, this is true only for VoIP and FTPI + VoIP models. If FTPII + VoIP model is implemented, eACS-MB surpass ACS-MS only slightly while SOS offers better result for FAP's position up to 5 m from the house boundaries.

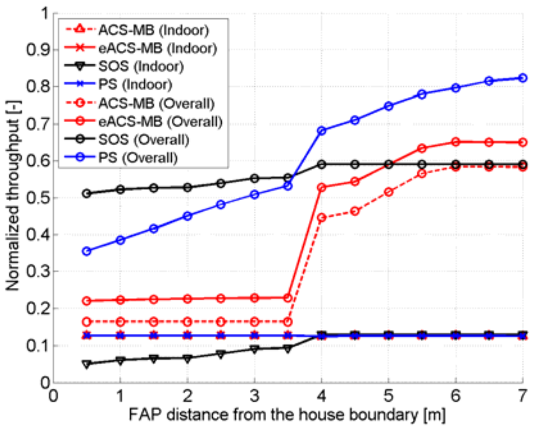
Figure 29 also demonstrates that the PS scheme outperforms all conventional schemes in term of overall throughput for VoIP and FTPI + VoIP traffic loads. In case of heavy traffic load, our proposed scheme has always better results but for SOS scheme. Nonetheless, PS is still better than SOS scheme if the FAP's distance from house boundaries is at least 4 m (for bandwidth equal to 3 MHz) or 1 m (for bandwidth equal to 10 MHz) respectively. Although the SOS outperforms our schemes for FAP's position closer to the sidewalk, the performance of SOS scheme in general terms is not satisfactory. The main reason is that the FAP's transmitting power is adapted in dependence on the number of mobility events. Thus, the CINR experienced by passerby UEs is very low as the signal strength received from MSB is only marginally higher than signal received from the FAPs, i.e., low efficient MCS has to be utilized.



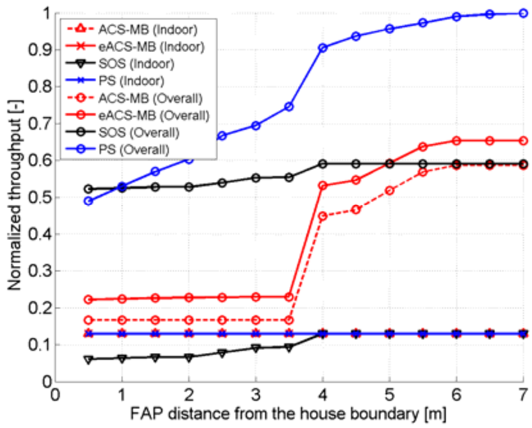
a) VoIP, 10 MHz



b) FTP I + VoIP, 10 MHz



c) FTP II + VoIP, 3 MHz



d) FTP II + VoIP, 10 MHz

Figure 29. Comparison of achieved throughput for individual schemes

Figure 30 depicts the mean value of FAP's transmitting power for selected scenarios considered in Figure 28. The highest transmitting power is reached for ACS-MB scheme, which is varying between 19 dBm and 6 dBm over the distance between the FAP and the house edge. The mean transmitted power of the proposed power control mechanism varies between 0 dBm to -18 dBm depending on current traffic model type, channel bandwidth, and FAP's position. All power control methods except of the SOS show gradual decrease of transmitting power if the FAP's location is moving from the house boundary to the centre. The mean transmitting power of FAP increases for SOS since this scheme attempts to maximize indoor coverage. Consequently, as the FAP's position is successively farther from the house boundary the transmitting power can be continuously increased while the interference to outdoor users is not. It is clear that in case of SOS scheme the mean transmitting power is always higher then PS for FAP's distance between 2.5 m and 7 m. In addition, also eACS-MB method achieves lower mean transmission power for FAP's location between 5 m and 7 m. Figure 30 further indicates that the proposed scheme has also a potential to save power energy.

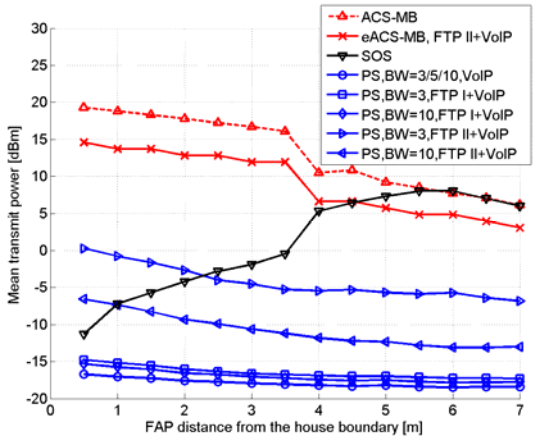
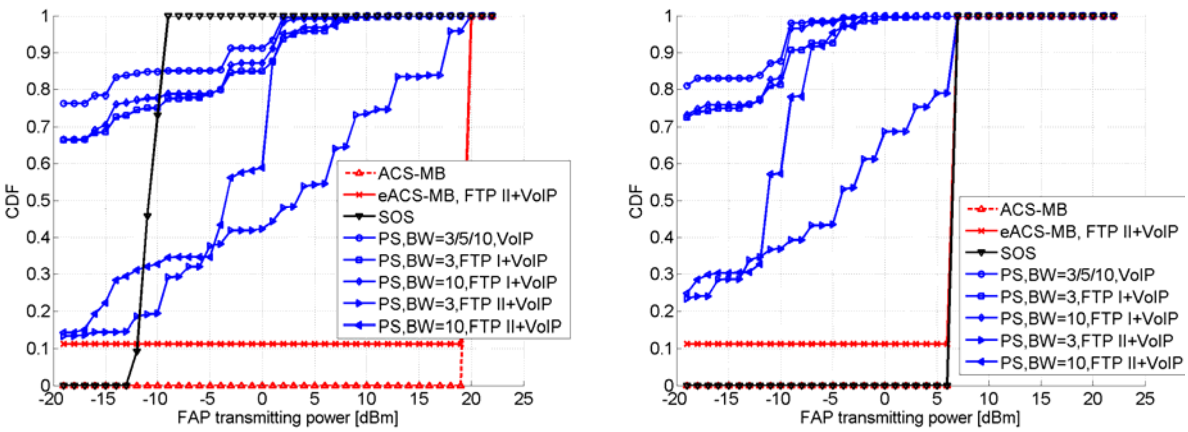


Figure 30. Mean transmit power of FAP, ΔP=2 dB

Figure 31 illustrates a CDF of FAP's transmitting power for two FAP's position. In general, the results are comparable to the outcomes described in previous figure. More than that, it is clear that the transmitting power in case of the proposed scheme is much more varying than in case of ACS-MB and SOS schemes. This is due to the fact that the proposed scheme adjusts dynamically transmitting power according current conditions.



a) b)

Figure 31. Distribution of FAP's transmitting power, distance of FAP from house boundary 0.5m (left figure) and 7m (right figure), ΔP=2 dB

4.2.9.3 Conclusion

The results demonstrate that the optimized PS mechanism significantly outperforms both evaluated ACS schemes. Despite of this, the PS is able to guarantee the same QoS to FAP's users as in case of ACS-MB or eACS-MB. When compared to the SOS trying to mitigate mobility events while maximizing indoor coverage, the results achieved by our power control method are always better as long as the generated traffic is at light or medium levels and sufficient amount of radio resources is allocated to the FAP. Nonetheless, with optimized power adaptation step equal to 2 dB, the PS outperforms SOS also at heavy traffic load if sufficient amount of radio resources is allocated to the FAP while it still enables the coverage of all users in the house. The further benefit of the proposed power control scheme can be seen in its potential to minimize overall power consumption by the FAP.

4.2.10 Optimization of power control mechanism

A performance of the power control based on frame utilization is highly influenced by several parameters and factors: target frame utilization ϑ_{target}, adaptation interval Δt, and power adaptation step ΔP. At the same time, the important aspect is how the algorithm should deal with the situation when FAP become overloaded.

4.2.10.1 Impact analysis of $\vartheta_{ttarget}$ and congestion strategies

The influence of power adaptation algorithm by above mentioned aspects is depicted in Figure 32. The Figure 32 illustrates the requirements of all FAP's users denoted as ϑ (upper figure) in dependence on FAP's transmitting power P_t (bottom figure). As long as the $\vartheta < 1$, all generated data are transmitted without any additional delay. However in the opposite case, the data has to be stored in FAP's buffer and thus a delay would be introduced.

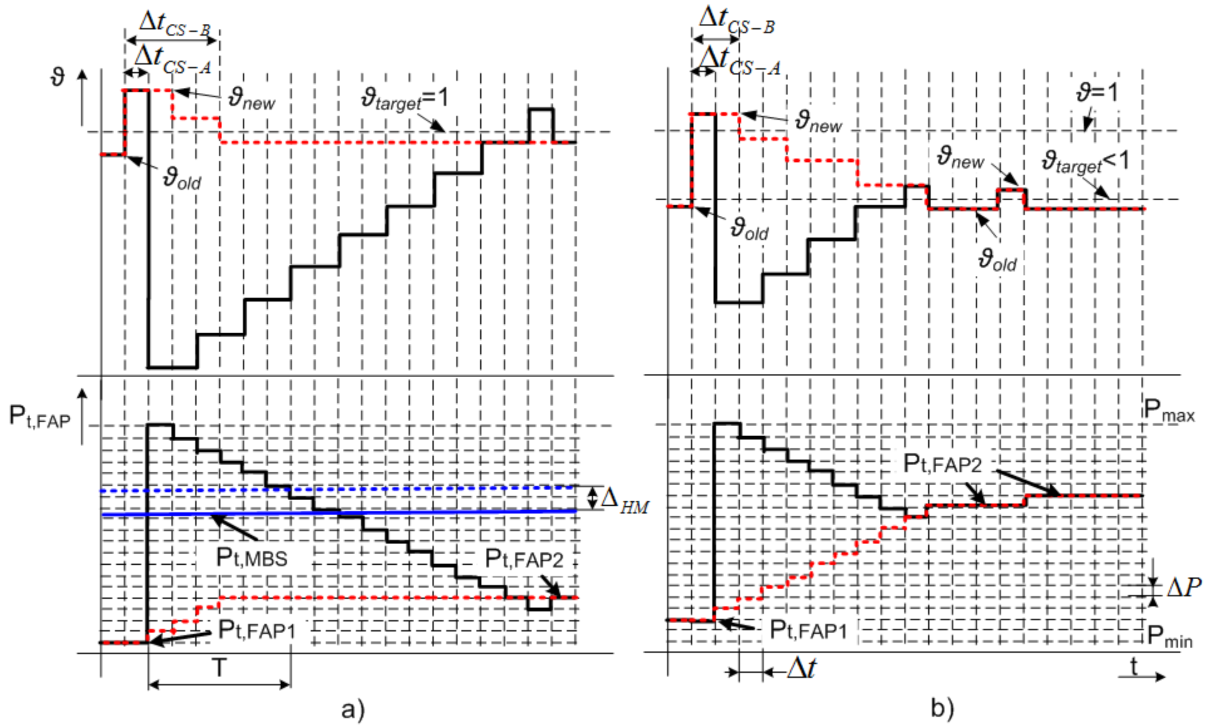


Figure 32. Impact of several aspects on power adaptation algorithm

Figure 32a shows the situation when $\vartheta_{target} = 1$ as it was assumed previous evaluations. In other words, the whole bandwidth allocated to the FAP is utilized. Consequently, the transmitting power can be set to lower values. It mitigates interference to neighboring FAPs and MBS's users. Still any increase of UEs' requirements or switching to more robust MCS by one or several users (e.g., due to lower signal quality) can temporally overload the FAP. Thus, the FAP is not able to transmit all data packets at designated time. This temporally decreases QoS experienced by FAP's users. In case of the first strategy, denoted as CS-A, the transmitted power of FAP is set to its maximal allowed transmitting power whenever FAP's become overloaded. In the subsequent steps, the power is continuously decreased until the FAP's buffer is emptied. This strategy is represented by solid black curve in Figure 32. The second congestion strategy, CS-B, deals with the FAP's overloading differently. Instead of setting the transmitting power to maximal value, the FAP increases its transmitting power gradually (in Figure 32 represented by dotted red curve).

The advantage of new CS-B over former CS-A strategy is that the probability of new mobility event initiation is lower. New mobility event is registered if:

$$P_{t,FAP} - u_{t,FAP}(t) > P_{t,MBS} - u_{s,MBS}(t) + \Delta_{HM}\ ,\ t \in \left(t, t + HDT\right) \quad (33)$$

where $P_{t,FAP}$ ($P_{t,MBS}$) is transmitting power of FAP (MBS), $u_{t,FAP}(t)$ ($u_{s,MBS}(t)$) represents radio channel characteristics (including path loss, shadowing, and fading), Δ_{HM} stands for hysteresis margin, and *HDT* represents Handover Delay Timer. Consequently, in case of CS-A, new mobility event is initiated on the following assumption:

$$T > HDT \text{ where } T = \frac{P_{\max} - P_{t,MBS} + \Delta_{HM}}{\Delta P} \times \Delta t \quad (34)$$

where P_{max} is maximum allowed transmission power of FAP. Since the FAP's power in case of CS-B is increased continuously, no mobility event occurs if:

$$P_{t,2} < P_{t,MBS} + \Delta_{HM} \quad (35)$$

where $P_{t,2}$ stands for FAP's transmitting power after adaptation (see Figure 32).

A possible drawback of CS-B over CS-A consists in longer overloading time caused by power adaptation algorithm. In case of CS-A, the overloading time inflicted by the power adaptation algorithm ($\Delta t_{CS\text{-}A}$) is at the most equal to Δt (it is assumed that FAP is always able to serve its users at least at P_{max}). If CS-B is utilized, a time during which the FAP is overloaded can be expressed as:

$$\Delta t_{CS-B} = \frac{P_{t,2} - P_{t,1}}{\Delta P} \times \Delta t \quad (36)$$

The overloading time caused by proposed CS-B can be notably reduced by consideration of higher ΔP. Nonetheless, higher ΔP brings another disadvantage as it reduces the number of possible FAP's discrete transmitting power levels, i.e., it is harder to utilize frame exactly at the selected ϑ_{target}. The second option for avoiding FAP's congestion or at least to mitigate its duration is by setting ϑ_{target} to the values lower than 1 (see Figure 32b) since the FAP is not temporarily overloaded if:

$$\left|\vartheta_{old} - \vartheta_{new}\right| < 1 - \vartheta_{\text{target}} \quad (37)$$

Hence the probability of FAP's congestion is decreased for lower values of ϑ_{target} since a difference between ϑ_{new} and ϑ_{old} could be higher without any overloading. However, the drawback of this approach is in higher transmitting power. The reason is as follows. The utilization of FAP's resources during frame *k* is calculated as:

$$\vartheta^{k} = \frac{n_{OH}^{k} + n_{D}^{k}}{n_{SC} \times n_{SMB}} \quad (38)$$

where n_{OH}^{k} and n_{D}^{k} represent the number of resource elements appointed to control information and data respectively, n_{SC} stands for the number of subcarriers and n_{SMB} represents the amount of OFDM symbols per frame. If the ϑ_{target} is decreased, the less radio resources are available and data has to be transmitted with higher efficiency since:

$$n_D^k = \sum_{j=0}^{n} \frac{TL_j^k}{\Gamma_j^k} \qquad (39)$$

where n is the number of active users attached to the FAP, TL_j^k is the amount of data send to user j, and Γ_j^k is transmission efficiency of j-th user. To transmit with higher Γ_j^k, the transmitting power of the FAP ($P_{t,FAP}$) has to be increased appropriately. Thus according to (33) the probability of new mobility events is higher.

The goal now is to find optimal settings of ϑ_{target}. To formally describe the problem, we denote two objection functions: $f_{me}(\vartheta_{target})$ as an objective function of number of generated mobility events, and $f_{ot}(\vartheta_{target})$ as an objective function of FAP's overloading time. The aim would be to find such ϑ_{target} when both objective functions are minimized. Nevertheless, higher values of ϑ_{target} decreases the $f_{me}(\vartheta_{target})$ while the $f_{ot}(\vartheta_{target})$ is increased. Since the minimum of these two does not correspond to the same value of ϑ_{target}, some tradeoff has to be found.

In addition, the influence of power adaptation algorithm when various adaptation intervals Δt are selected is derived. On one hand, short duration of Δt cuts down the time of adaptation. On the other hand, signaling overhead due to reporting and computational complexity reciprocal in proportion to the length of Δt. To that end experimental simulations are performed to determine appropriate setting of ϑ_{target}, Δt.

4.2.10.2 Simulation results

The performed simulations are done in MATLAB under the same assumption as described in 4.2.9.1 and 4.1.4 respectively. The first objective of performed simulations is to analyze the impact of different levels of ϑ_{target} for both congestion strategies. The investigation is primarily focused on performance of power control algorithm based on frame utilization. Nevertheless, for certain point of reference and comparison, two additional schemes similarly as in section 4.2.9.2. While the first one represents auto configuration scheme (ACS) the second one corresponds to self optimization scheme (SOS).

If the traffic is low, the number of generated mobility events is approximately the same independently on selected ϑ_{target} as indicates Figure 33. In addition, no distinguishable difference between CS-A and CS-B strategies is observed. The reason is that at low traffic load, the FAP is most of the time underloaded. Thus, the FAP's transmitting power is practically the same for all investigated values of ϑ_{target}. The situation is different for higher FAP's loads. The number of initiated mobility events is increasing with lowering level of ϑ_{target}. This is caused by the fact that the efficiency of the algorithm is proportionally decreased as well (see explanation in previous section). Nonetheless, the amount of mobility events is still not changing significantly. Furthermore, the Figure 33 demonstrates negligibly higher performance of CS-B over CS-A for all considered levels of ϑ_{target}.

Figure 33 also indicates that the worst performance is obtained always for ACS scheme. If power control based on frame utilization is compared to SOS scheme, the results for FAP's position close to the house boundary are in favour of SOS. Nonetheless, the drawback of SOS consists in worse QoS experienced by FAP's users.

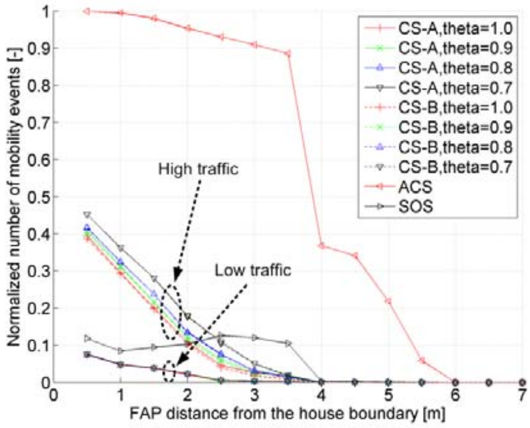


Figure 33. Impact of various ϑ_{target} on performance of power adaptation algorithm based on frame utilization

As already described above, the possible drawback of the power adaptation algorithm based on frame utilization is that it can temporally overloads the FAP. Table 7 depicts the results for both congestion strategies at low and high traffic. It is demonstrated that the FAP's overloading is practically nonexistent for low traffic as the total amount of overloading time is just up to 0.05 s (i.e., duration of five frames) out of 20 000 s of simulation time. The same outcomes can be stated for the high traffic generated by users. Although the time during which the FAP is overloaded increases as well, still only small portion of overall simulation time is negatively affected (up to 6.6 s out of 20 000s). If both congestion strategies are compared, the CS-A slightly outperforms the CS-B. Nevertheless, from the global point of view the FAP's overloading time is insignificant for all investigated scenarios. Moreover, the overloading time can be effectively reduced by selection of lower target frame utilization ϑ_{target}. However this is at the cost of slight rise of mobility events.

	Target frame utilization [-]			
	0.7	**0.8**	**0.9**	**1.0**
CS-A (low traffic)	0.02	0.02	0.05	0.05
CS-B (low traffic)	0.02	0.02	0.05	0.05
CS-A (high traffic)	0.68	3.1	5.39	6.21
CS-B (high traffic)	1.01	3.8	6.38	6.6

Table 7. FAP's overloading time in seconds

So far we assumed that the adaptation period Δt is set to 10 ms, which corresponds to the duration of one LTE-A frame. In other words, the FAP has to be able to change its transmitting power every 10 ms as well. In order to do that, the UEs should report the channel quality experienced in downlink every adaptation interval. To decrease signaling overhead due to reporting and also to lower computational complexity of the algorithm, the adaptation interval Δt should be prolonged.

The performance of both congestion strategies over various adaptation periods Δt is illustrated in Figure 34. For this purpose, all target frames utilization ϑ_{target} as in Figure 33 were considered. Since the best results are obtained for target frame utilization ϑ_{target} = 0.9, only those are depicted in Fig. 6 and Table III. In case of light traffic load, the performance of the algorithm is practically not affected similarly as in Figure 33. Independently on Δt, the number of observed mobility events is roughly the same for both congestion strategies. When the traffic load is increased, a prolongation of Δt have negative impact on congestion strategy CS-A. On the other hand, performance of CS-B remains unaffected by Δt while efficiency of CS-A is decreasing with rising Δt. The CS-A is negatively affected since the FAP's transmitting power is always set to the maximal value during congested state.

Nonetheless, the time necessary for decrease of transmitting power to appropriate value (in Figure 32, this value is denoted as $P_{t,2}$) is directly proportional to Δt in case of CS-A. As a consequence, more mobility events are initiated than in case of CS-B.

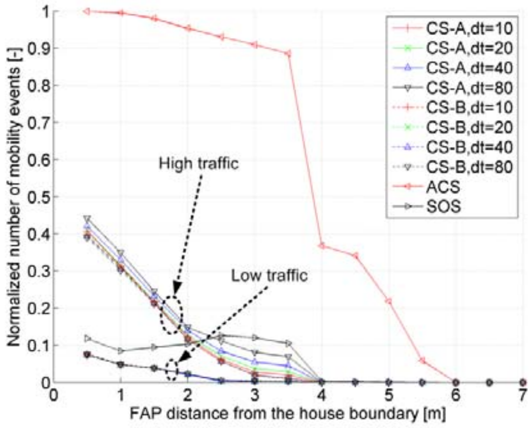


Figure 34. Impact of various Δt on performance of power adaptation algorithm based on frame utilization

The better performance of CS-B over CS-A in Figure 34 is at the cost of minor prolongation of FAP's overloading periods. This is depicted in Table 8. At low traffic loads, the overloading is negligible and varies between 0.05 s and 0.6 s. If the traffic load is increased, the FAP is overloaded much longer (up to 48.39 s for the worst case, i.e., for CS-B when Δt is set to 80 ms). Nevertheless, still the overloading time is insignificant taking into account the simulation duration of 20 000 s, i.e., the FAP is congested up to 0.24 % of the whole simulation time.

	Δt [ms]			
	10	**20**	**40**	**80**
CS-A (low traffic)	0.05	0.12	0.29	0.52
CS-B (low traffic)	0.05	0.13	0.33	0.6
CS-A (high traffic)	5.39	11.72	22.9	42.15
CS-B (high traffic)	6.38	11.88	24.38	48.39

Table 8. FAP's overloading time in seconds

4.2.10.3 Conclusion and discussion

The following remarks can be defined according to above the performed simulations. At light traffic load, the performance of power control mechanism is practically the same no matter which ϑ_{target}, Δt or congestion strategy is selected. At heavy traffic load, the lower target frame utilization ϑ_{target} results in the higher amount of mobility events. Nevertheless, the FAP's overloading time could be shortened at the same time. Consequently, setting target frame utilization to 0.9 seems to be as eligible compromise for all scenarios. By prolonging adaptation period Δt, the proposed CS-B is not affected in term of mobility events. On the other hand, the amount of mobility events rises with Δt for former CS-A congestion strategy. Regarding the FAP's overloading time, the proposed CS-B performs only slightly worse than CS-A.

From the above mentioned could be derived final recommendations. If the reporting period is set to 10 ms, it is always better to use former CS-A as the number of mobility events is comparable to proposed CS-B while the FAP's overloading time is shorter. However, if the main objective is to decrease signaling overhead and algorithm computational complexity, it is more efficient to use CS-B. In this case the number of mobility events is significantly lower than in case of CS-A and simultaneously the FAP's overloading time is prolonged only marginally comparing to CS-A.

As a possible further research could be aimed at the investigation how the performance of the power control algorithm is affected by varying FAP's backbone capacity.

4.3 Multicast Broadcast & Multicast Services

4.3.1 Introduction

The MBMS is a unidirectional point-to-multipoint bearer service in which data is transmitted from a single source entity to multiple recipients [3GPP TS 22.146 V6.6.0]. The main objective of the MBMS is to deliver multimedia service with the efficient management of core network and radio resources, reusing as much of the existing functionality as possible.

For conventional Macro BS (MBS), radio resources are managed to ensure channel assigned proportionally according to channel availability and QoS requirements. In addition to the advanced QoS mechanism implemented in BS, a mobile operator usually implements end-to-end QoS across its network from Radio Access Network (RAN) to its mobile core network. Hence there are almost no performance issues in the backhaul since most mobile operators secure a Service Level Agreement (SLA) with the transport/link provider. This is not the case in FAP where the traffic will traverse across network and may experience congestion or different treatment depend on SLA between end-user, ISP and Mobile Operators.

4.3.2 E-MBMS

The architecture of E-MBMS (MBMS in LTE network) consists of three domains, i.e., User Equipment (UE) domain, evolved UMTS Terrestrial Radio Access Network (e-UTRAN) domain, and Evolved Packet Core (EPC) domain (see Figure 35). The UE domain consists of the equipment employed by the user to access the MBMS services. Within e-UTRAN, the evolved NodeBs (eNodeBs or base stations) are the collectors of the information that has to be transmitted to users over the air-interface. The Multi-cell/multicast Coordination Entity (MCE) coordinates the transmission of synchronized signals from different cells and is responsible for the allocation of the same radio resources, used by all eNodeBs in the MBSFN area for multi-cell MBMS transmissions. Besides allocation of the time / frequency radio resources, MCE is also responsible for the radio configuration, e.g., the selection of the MCS [3GPP, 2010c; Holma09].

The EPC consists of five main nodes. These are the Mobility Management Entity (MME), the Serving Gateway (S-GW), the PDN Gateway (P-GW), the e-MBMS Gateway (e-MBMS GW) and the evolved Broadcast Multicast Service Center (e-BM-SC). The last two nodes are associated only with e-MBMS. The MME is the key control-node for the LTE access-network. The MME executes and coordinates all major control functionalities of LTE. At first, MME is responsible for the secure signaling procedure of LTE, which is called Non Access Stratum (NAS) signaling. Secondly, MME controls the UE handover procedures. Furthermore, it coordinates the UE tracking, paging and polling procedures of LTE. Additionally, MME handles the UE reachability procedures (CONNECTED, IDLE). The MME is also responsible for the authentication and authorization functions both for UEs as well as for authentication of the interconnection of LTE with external Packet Data Networks (PDNs). The control of the roaming procedures is another basic functionality of MME. A warning message transfer function is also implemented in MME providing in that way a more optimized selection of appropriate eNodeBs for the transmission of the data. Last but not least, MME is responsible for controlling the radio bearer management functions including dedicated bearer establishment [3GPP, 2010b; 3GPP, 2010c].

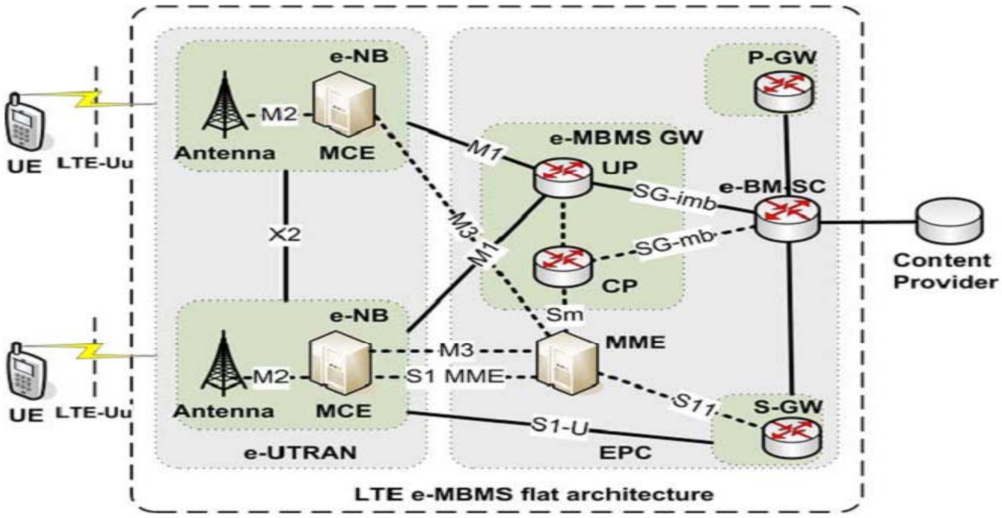


Figure 35. e-MBMS flat architecture.

The S-GW routes and forwards user data packets, while also acting as the mobility anchor for the user plane during inter-eNodeB handovers and as the anchor for mobility between LTE and other 3GPP technologies. For idle state UEs, the S-GW terminates the downlink (DL) data path and triggers paging when DL data arrives for the UE. It manages and stores UE contexts, e.g., parameters of the IP bearer service, network internal routing information. It also performs replication of the user traffic in case of lawful interception [3GPP, 2010b; 3GPP, 2010c].

The P-GW provides connectivity from the UE to external packet data networks by being the point of exit and entry of traffic for the UE. A UE may have simultaneous connectivity with more than one PGW for accessing multiple PDNs. The P-GW performs policy enforcement, packet filtering for each user, charging support, lawful Interception and packet screening. Another key role of the PGW is to act as the anchor for mobility between 3GPP and non-3GPP technologies such as WiMAX and 3GPP2 [3GPP, 2010b; 3GPP, 2010c].

The e-MBMS GW is physically located between the e-BM-SC and e-NBs and its principal functionality is to forward the MBMS packets to each e-NodeB transmitting the service. Furthermore, e-MBMS GW performs MBMS Session Control Signaling (Session start/stop) towards the e-UTRAN via the MME. The e-MBMS GW is logically split into two domains. The first one is related to control plane, while the other one is related to user plane. Likewise, two distinct interfaces have been defined between e-MBMS GW and e-UTRAN namely M1 for user plane and M3 for control plane. M1 interface makes use of IP multicast protocol for the delivery of packets to e-NBs. M3 interface supports the MBMS session control signaling, e.g., for session initiation and termination. The e-BM-SC is the entity that is in charge of introducing multimedia content into the LTE network. For that purpose, the e-BM-SC serves as an entry point for content providers or any other broadcast/multicast source, which is external to the network. An e-BM-SC serves all the e-MBMS GWs in a network [3GPP, 2010b; Holma09].

Regarding the air (or LTE-Uu) interface, in MBSFN the transmission takes place from a time-synchronized set of e-NBs using the same resource block. The OFDM symbols in MBSFN contain a Cyclic Prefix (CP), which however is slightly longer than the CP used in conventional transmissions. This enables the UE to combine transmissions from different e-NBs located far away from each other [3GPP, 2007b]. Moreover, MBSFN uses two logical channels (in downlink), namely Multicast Traffic Channel (MTCH) and Multicast Control Channel (MCCH). The MTCH is a Point-to-Multipoint (PTM) downlink channel for transmitting data traffic to the UEs residing to the service area. On the other hand, MCCH is a PTM downlink channel used for transmitting MBMS control information from the network to UEs and is associated to one or several MTCHs. MCCH and MTCH are only used by

UEs that receive MBMS traffic. Additionally, both MCCH and MTCH are mapped on the Multicast Channel (MCH), which is a transport channel at the Medium Access Control (MAC) layer. MCH is a broadcast channel that supports semi-static resource allocation e.g. with a time frame of a long CP. MCH is mapped to the Physical Multicast Channel of the physical layer [3GPP, 2009; 3GPP, 2010b].
The introduction of the MBSFN feature in the set of LTE transmission techniques has triggered a set of experiments that have been performed in the context of 3GPP and have investigated the efficiency of the radio techniques that can be employed in order to provide the MBMS services [3GPP, 2007a; 3GPP, 2007c; 3GPP, 2007d]. These experiments have been conducted through network simulations and have provided useful information about the relative efficiency of different approaches for the provisioning of MBMS services. Different means to provide MBMS services have been evaluated including the following techniques:

a) Point-to-Point (PTP) provisioning of MBMS services: this corresponds to mapping the MBMS service to Downlink Shared Chanel (DL-SCH) and includes the possibility to apply link adaptation and Hybrid Automatic Repeat-reQuest (ARQ).

b) MBSFN-based multi-cell transmission using MCH.

c) PTM provisioning of MBMS services on a per-cell basis with no UE Layer 1 feedback. RAN1 has, at this stage, not made any specific assumptions whether this corresponds to DL-SCH transmission addressing multiple UEs or single-cell MCH transmission.

d) PTM provisioning of MBMS services on a per-cell basis with a possibility for Hybrid ARQ UE feedback also for point-to-multipoint transmission.

e) PTM provisioning of MBMS services with interference reduction by not transmitting on neighboring cells.

f) PTM provisioning of MBMS services on a per-cell basis with a possibility for UE feedback, thus enabling link adaptation and Hybrid ARQ also for point-to-multipoint transmission.

Many simulation experiments for E-MBMS have been conducted for various UE densities and geometries of the UE drop locations, in order to examine the LTE network topology. The previous performance evaluation had demonstrated the advantages of the PTP and MBSFN-based techniques, providing significant benefits over the PTM techniques, in terms of spectral and resource efficiency, coverage and complexity of specification [3GPP, 2007a; 3GPP, 2007d]. Moreover, the MBSFN-based multi-cell technique is able to deliver the highest data rate in the central cells of the deployments [3GPP, 2007a]. It should be noted that the PTM transmission techniques have been proved efficient only in cases of low UE densities (less than 1.3 UEs/sector) [3GPP, 2007d] or when the UE's subscribing to the MBMS service in question are restricted to occupy only a single cell or a very small number of cells [3GPP, 2007a].

This study focuses on the E-MBMS application in LTE based Femtocell network, which still open for research, given that this kind of study hadn't been done yet. Consequently, the following sections will focus on the transmission techniques of E-MBMS and evaluate the performance among each transmission techniques.

4.3.3 Multipoint Communication

Point-to-multipoint or more simply multipoint communications is a term used in the telecommunications to refer to communication that is accomplished via a multipoint connection, providing a communication link between a single source and multiple receivers.

Many applications involve one-to-many or many-to-many communications, where one or more sources are sending data to multiple receivers. Such multipoint transmissions can be achieved in three different ways: unicast where a separate copy of the data is delivered to each recipient, broadcast where a data packet is forwarded to all portions of the network and multicast where a single packet is addressed to all intended recipients and the network replicates packets only as needed.

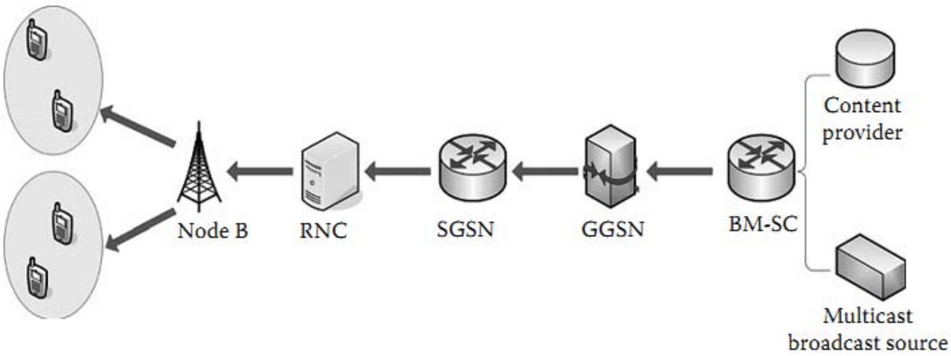


Figure 36. Point-to-Multipoint in UMTS

4.3.3.1 Unicast mode

In networking, the fundamental method of communication is between two hosts, or unicasting. Such one-to-one sessions offer a great deal of control of the data traffic between the source and receiver, allowing for acknowledgement of receipt, requests for retransmission of data, changes in transmission rate and so on. Figure 37 illustrates the point-to-point nature of unicast.

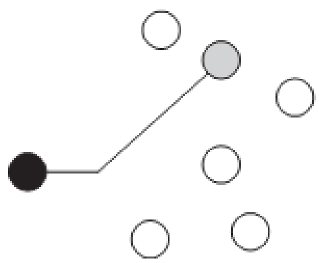


Figure 37. Unicast as one-to-one communication

In multipoint unicasting, a source sends an individual copy of a message to each recipient. If five individuals in a workgroup wish to receive a copy of the same file using FTP, the server would send the file to each of the five recipients separately, using 5 times as much bandwidth as for a single transfer. This is wasteful of network bandwidth.

Point to Point transmission in LTE

The use of Orthogonal Frequency Division Multiplex (OFDM) [Holma09] for downlink transmission in Long Term Evolution (LTE) of UMTS enables flexible frequency domain scheduling. In each transmit time interval (TTI) of 1 ms, one or more RBs with a granularity of 180 kHz corresponding to 12 subcarriers can be assigned to a user equipment (UE). The number of available sub bands depends on the total downlink system bandwidth. Based on reference symbols the UE can measure the reception conditions in each sub band. In basic configurations of PTP transmission, active UEs periodically report their reception conditions as channel quality indicators (CQI) to the serving eNodeB. This concept is referred to as multiband CQI reporting because it provides channel quality information for multiple sub bands, thus allowing for channel-dependent scheduling. This means that sub bands indicating good channel qualities are assigned to the corresponding UEs first, aiming at the maximization of the transmit rate. Consequently, the bandwidth and frequency range assigned to a UE may vary. The appropriate MCS for the group of RBs is dynamically selected based on the CQIs aggregated in the frequency domain.

Due to inaccurate measurements, user mobility and traffic fluctuations, rate adaptation errors may occur resulting in either unnecessarily high robustness of the transmission or Layer 1 block errors. In order to compensate for inaccuracies of MCS an N-channel stop-and-wait Hybrid Automatic Repeat reQuest (HARQ) protocol [3GPP R1-071049] has been introduced in LTE. If the decoding of a transport block was successful, the receiver sends a positive acknowledgment (ACK) to the transmitter; otherwise it sends a negative acknowledgment (NACK). Information from previously failed attempts is saved in a buffer and soft combined with successive information before a decoding attempt is started. Consequently, the transport block becomes more reliable with each retransmission. Especially in environments with rapidly changing channel conditions, HARQ significantly improves the system performance. Since there is a fixed time alignment between the transmission of a transport block and the reception of a HARQ feedback, only a single bit has to be allocated for a HARQ status report.

4.3.3.2 Broadcast mode

Under certain circumstances, it can be more efficient to transmit one copy of a message to all network nodes and let the receiving nodes decide if they want the message. Distributing the task of duplicating the packets among the network nodes rather than focusing the task at the sender's host machine is advantageous for the sender. This is referred to as broadcasting. The illustration of one-to-all nature of broadcast is shown in Figure 38. There are many network hardware technologies that include mechanisms to broadcast packets to multiple destinations at the same time. With Ethernet, broadcast delivery can be accomplished with a single packet transmission on the wire.

One significant feature of broadcasting is that it relieves the source from the task of duplicating packets that are destined for multiple recipients. The source transmits a single copy of the packet to the appropriate broadcast address and the network devices take over, duplicating the packet as needed to cover the network.

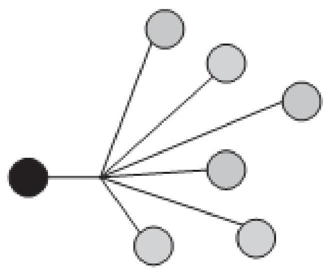


Figure 38. Broadcast as one-to-all communication

4.3.3.3 Multicast Mode

Multicast is the delivery of information to a group of destinations simultaneously using the most efficient strategy to deliver the messages over each link of the network only once, creating copies only when the links to the destinations diverge. The Multicast falls between unicast and broadcast. Rather than sending data to a single host or to all hosts on the network, multicast aims to deliver data to a select group of hosts (see Figure 39). The host group is defined by a specific multicast address.

Once a host group is set up and the sender starts transmitting packets to the host group address, the network infrastructure takes on the responsibility for delivering the necessary data streams to all members of the group. Only one copy of a multicast message passes over any link along the delivery path in the network. Copies of the message are only made when paths diverge at a router, thus helping to conserve bandwidth. In multicast, as in broadcast, the source of a message usually does not know which recipients are within the group or the state of the data delivery.

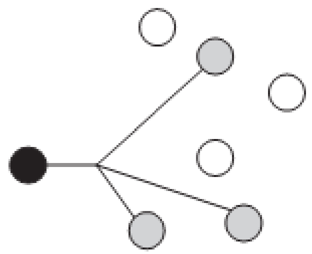


Figure 39. Multicast as one-to-all communication

4.3.4 Principle of Single Frequency Network (SFN)

Early implementation of MBMS in the UMTS network relies only on two types of transmission schemes, i.e., Point to Point and Point to Multipoint. As mentioned earlier in section 4.3.2, MBMS implementation in LTE (which called E-MBMS) supports a new transmission scheme called MBSFN (MBMS over Single Frequency Network). The MBSFN has therefore been proposed for UTRAN and LTE, in [3GPP R1-071049] and [TS 23.246 V6.3.0] respectively, to improve the performance of MBMS.

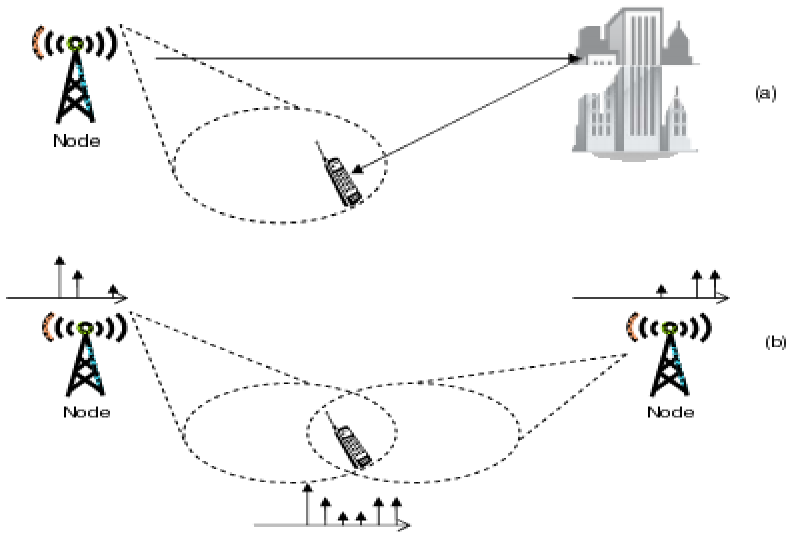


Figure 40. a) multi-path propagation (b) MBSFN signal combining based on constructive interference

In the SFN technology, all the base stations transmit the same signal at the same time and over the same frequency channel to UEs. Therefore, the base stations are required to be tightly time-synchronized. In this case, the transmissions received from multiple cells will, as seen from the UE, appear as a single transmission subject to severe multi-path propagation as shown in Figure 40a. Thus, it overcomes the two mentioned shortcomings of MBMS by transforming destructive interferences (i.e., ISI) to constructive interferences. In this process, the received signals from different cells are combined at the UE as illustrated in Figure 40b.

MBSFN Area Configuration

We define the MBSFN area as the group of cells that contain UEs, which requests media (the interested UE drop location cells) plus any number of assisting cells. A cell is assumed to be assisting when it broadcasts MBSFN data while it does not actually contain any users that request any media service. Although their Spectral Efficiency (SE) is not useful (i.e., they do not contribute to the SE of the system), assisting cells may increase the SE of nearby MBSFN cells by constructive combination of their transmissions. This is the main difference between MBSFN and PTM. The MBSFN transmissions are synchronized so their combination can be constructive while PTM transmissions cause interference to any other nearby transmission. If an area is completely surrounded by assisting neighboring cells then we say that it is surrounded by an assisting ring.

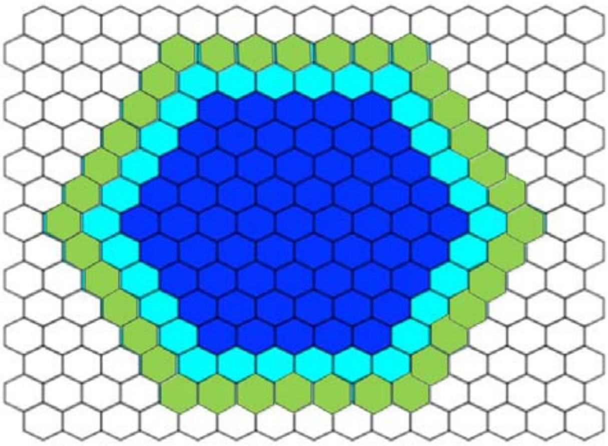


Figure 41. Example topology with 2 assisting rings

Figure 41 illustrates a MBSFN network topology. The dark blue cells are interested UE drop location cells that contain users requiring the MBSFN data, while the light blue cells are assisting cells, which form two assisting rings. In the rest of the document, we call this kind of network deployment as AAI (using the terminology from [de la Roche 2010], meaning that two rings around the interested UE drop area are assisting and the third one is interfering). In the same manner we define all cases from III (three interfering rings) to AAA (three assisting rings).

Time Synchronization of Transmitters in SFN

In a single frequency network all the individual transmitters must be exactly time synchronized. Every transmitter must broadcast absolutely identical OFDM symbol at the same time. The LTE modulation is structured in frames, one frame is being composed of 32 OFDM symbols. Four frames make up one so-called super-frame and two super-frames make up so-called mega-frame (in the mode 2k four super-frames). With regard to different time duration of the OFDM symbol, which depends on the parameters of used modulation and encoding (mode, i.e., number of carriers, code rate, guard interval etc.), the time duration of single frame can also be different.

Time synchronization of the all transmitted packets in the transport stream of the final data multiplex is ensured by the time signal 1 pps (pulse per second), which is acquired from the core network. This signal controls time synchronous insertion of the special packet MIP (Mega-frame Initialization Packet) into the transport stream at the beginning of every mega-frame. Time synchronization needed to synchronize the initialization of multimedia packet received by users because the received packets different in timing. The differences occur because in SFN, the users receive the same multimedia packets from multiple Base Stations.

4.3.5 Evaluation of E-MBMS in Femtocell Network

This section provides simulation results of PtP, PtM and SFN in macrocell and femtocell network. The performance evaluation will be assessed for a residential environment [FemtoForum]. The objective of the study is to compare the performance of MBMS and MBSFN between two networks,

4.3.5.1 System Model

The study was conducted using the OPNET simulation tools with LTE specialist Module. We are using 3 MBS and 5x5 grid FAPs with each grid size is 10m x 10m [Femto Forum] as illustrated in next figure.

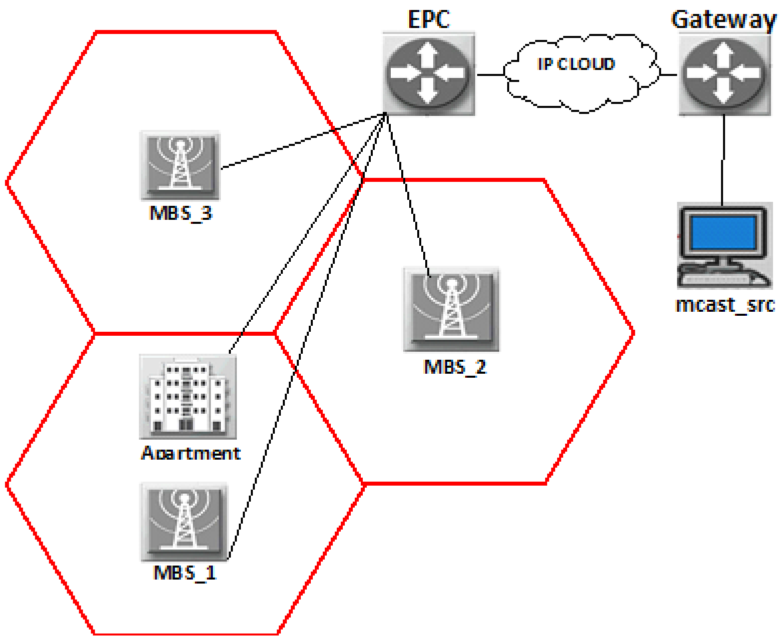


Figure 42. Network Model

The distance between MBS-1 and the apartment is assumed 200m [Femto Forum]. The video source is taken from the same source, i.e., Mcast_src. The BM-SC function is assumed to be integrated in the EPC node. The UEs were assumed to be a cell phone, therefore the simulation used a low resolution video, using H.264 codec. The video was takem from video trace from http://trace.eas.asu.edu/ (Sequence: Sony (Demo), Resolution: 352x288, FPS: 30.0, Frames: 17664, Encoder: JSVM (9.15)). Other parameters are showed in Table 9.

All users are indoor users and there were also assumed no user mobility, and the position of each user was deployed as random position with uniform distribution. All users access the same video source and use indoor propagation model from ITU-R P.1238-6 [ITU1238]. There are no MBS users in this simulation. Figure 43 illustrates the users positions for 5 users per FAP case, generated randomly with uniform distribution. Each simulation for PtP, PtM and SFM mode uses the same user position. It was assumed that in SFN transmission mode, all MBS and FAP use the same frequency. It was also assumed that no issues in the femtocell network (e.g. no bottleneck at backhaul).

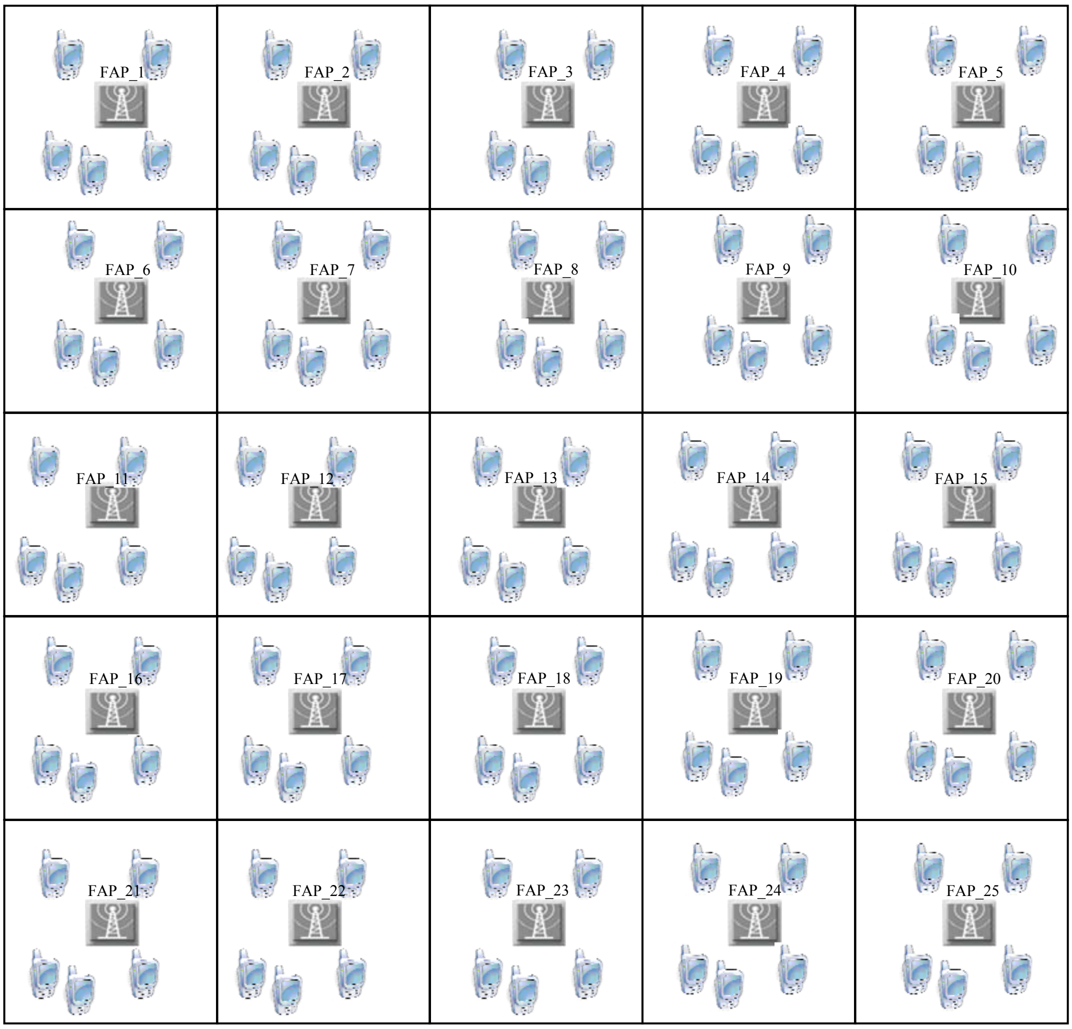


Figure 43. User Distributions in 5x5 grid

Parameter	Value
Cellular Layout (Macrocell)	Hexagonal grid, 3 cell site
Cellular Layout (Femtocell)	5 x 5 grid FemtoForum[FemtoForum 2009]
Radius Macrocell	500 m
Femtocell	10 x 10 m
Femtocell Transmit Power	20 dBm
Macrocell Transmit Power	43 dBm
System Bandwidth	10 MHz
Carrier Frequency	2 GHz
Duplexing	FDD
Propagation Model	TU-R P.1238-6 [ITU1238]

Table 9. System settings

The evaluations are conducted for 3 scenarios based on the transmission mode of the video, i.e., PtP, PtM, and SFN. Each transmission was evaluated with the addition of users on each grid, starting from 1 user to 5 users and using Macro Base Station network (without Femtocell) and with Femtocell network.

4.3.5.2 Simulation Result

The first result from the simulation shows the comparison of the video data rate (in kbps/user) received by the UE requesting Multimedia services. Figure 44 shows the result of the simulation for PtP, PtM and SFN transmission mode in both non femtocell network (no FAP implemented in the building) and femtocell network (FAP implemented in the building).

It can be seen from the graphics that the SFN transmission mode produces higher video bit rate compared to other transmission modes (PtP and PtM). The PtP transmission have higher video bit rate from the other transmission modes in case there was only 1 user active. As the number of users increases, video bit rate of PtP drops. It also can be seen that the femtocell network can support higher video bit rate in SFN and PtP mode, but not in PtM mode. Not like in SFN mode, the existence of femtocell network generates more nonconstructive interference in PtM mode.

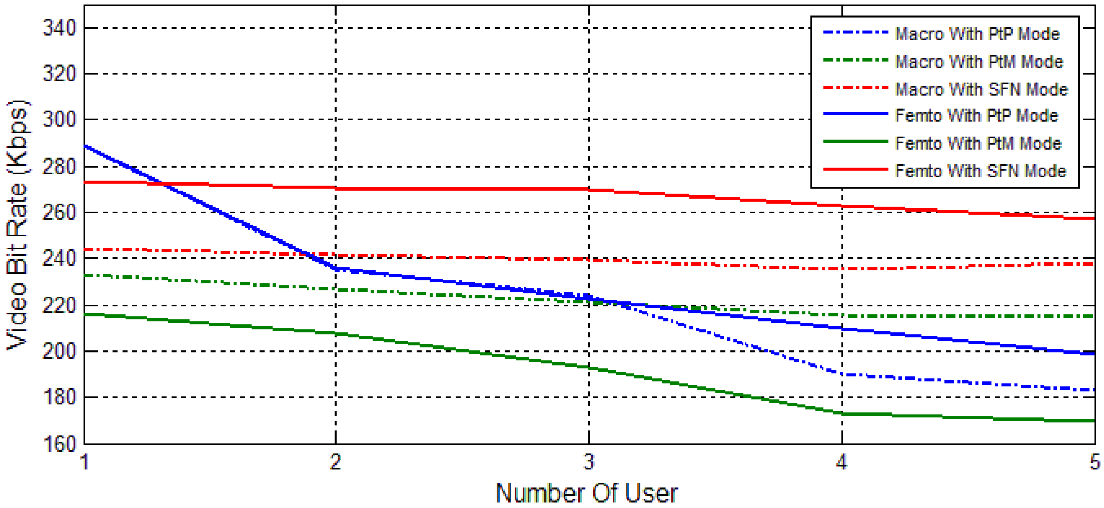


Figure 44. Received Video Bit Rate (kbps/user)

Figure 45 illustrates the BLER of each transmission mode of MBMS, both in femtocell network and non femtocell network. The BLER is the average BLER per user. The graphic shows that SFN mode produce lower BLER compared to other transmission modes. This can happen because in PtP mode, along with the increasing number of users, the resource block also increased, this will increase the transmitting power hence also increase significantly the interference level of all FAPs and MBS. In PtM mode, the increasing number of resource block is minimized by sharing resource block for all users in a group. On the other hand, the SFN mode because of the implication of synchronization, it increases the orthogonality of resource blocks which minimize the interference and produce the best BLER.

The comparison between femtocell and non femtocell network shows the advantages of femtocell network in delivering eMBMS in term of lower BLER in general. Other graphics in Figure 46 shows the packet drops for each transmission modem, which shows in general the same results.

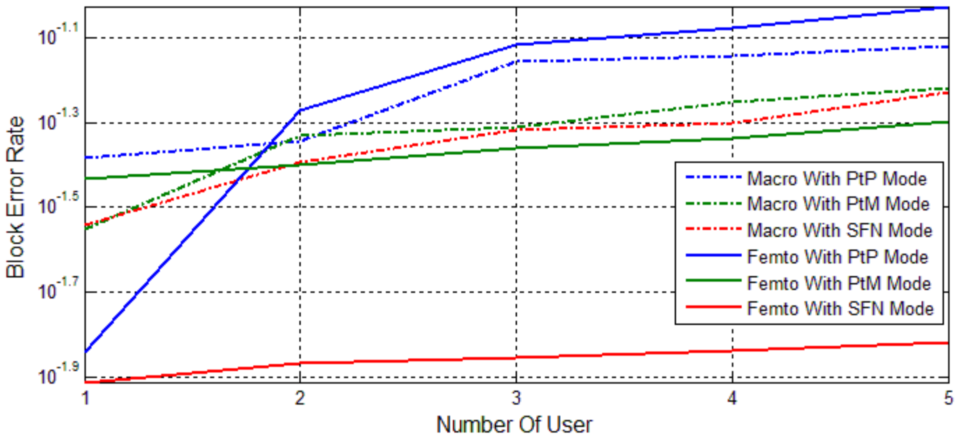


Figure 45. Block Error Rate

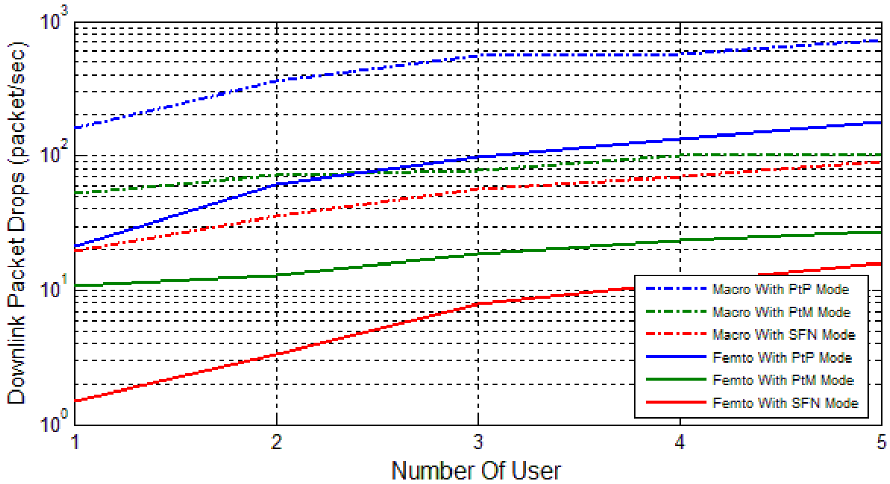


Figure 46. Downlink Packet Drop

Figure 48 shows the Reference Signal Received Quality (RSRQ) for each transmission mode. The use of femtocell network has less value of RSRQ compared to the MBS implementation. The figure also shows that PtP has less value of RSRQ compared to the other transmission modes.

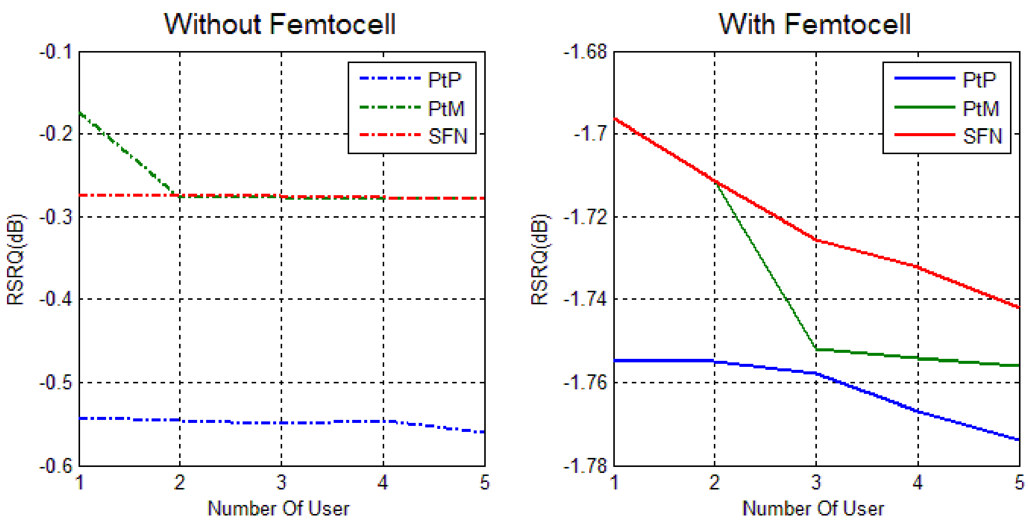


Figure 47. RSRQ Associated Base-Station

4.3.5.3 Conclusion

From the performed simulation, some conclusion can be drawn as mentioned in the following remarks. In term of comparing MBMS transmission techniques, SFN shows good performance compared to other techniques. It demonstrates the ability to have the highest video data rate, high SNR and low Block Error Rate. SFN shows the stability of performance, regardless the number of users is requesting multicast multimedia services. On the other hand, other techniques can also be elaborated such as PtM, which is simpler to implement, yet have the ability of good SNR and also low Block Error Rate and acceptable video data rate especially in macro network. In term of comparing the MBMS implementation between femtocell and macro cell, generally the simulation demonstrates the benefits of implementing MBMS in femtocell network. As PtM mode can be promoted also as one of the transmission mode of MBMS in femtocell, it need more advance algorithm or addition of FEC (Forward Error Correction) in order to improve the performance.

As a possible further research could be aimed at the investigation how the performance of MBMS can be improved, not only for each transmission mode, but also can be investigate the new algorithm used to combine these transmission mode to effectively deliver MBMS in the femtocell network.

4.4 Identification of femtocells

The Physical Cell identity (PCI) should be selected in such way to avoid a collision with respective to neighboring cells. Traditionally, the proper PCI is derived from radio network planning and it is part of the initial base station configuration. The PCI assignment should fulfill the following two conditions [3GPP TS 36.902]:

a) collision-free, i.e., the PCI is unique in the area that the cell covers

b) confusion-free, i.e., a cell does not have neighboring cells with identical PCIs

The PCI is an essential configuration parameter of a radio cell. Since the available number of unique PCI is limited (there are 504 PCIs available in LTE [3GPP TS 36.211]), a configuration scheme, which properly configures the parameter in each cell, is needed to ensure proper operation of the radio network. However, it is not always possible to guarantee confusion-free in a dense urban deployment scenario such as FAPs deployment under a MBS as the number of PCIs are limited. When confusion-free requirement cannot be met, it is still desirable to assign a PCI in such way that the occurrence of confusion and its effect are minimized.

An example of collision and confusion scenarios is shown in Figure 48. There are two FAPs having the same PCI (FAP_A, FAP_B) under coverage of one MBS. When receiving such PCI, the MBS does not know to which FAPs a UE is refereeing to. As a result, handover procedures, for example, from MBS to FAP_A/FAP_B cannot be properly supported. Moreover, these two FAPs would interfere and the communication would not be even possible. The confusion scenario is illustrated by FAP_E that borders FAP_C and FAP_D, both having the same PCIs. As in the collision case, if a UE sends a PCI to such FAP_E, the FAP is confused. Notice that the Figure 48 illustrates a FAP scenario example but the confusion scenario is applicable to whatever type of cell, i.e., micro, macro, pico or femto cell.

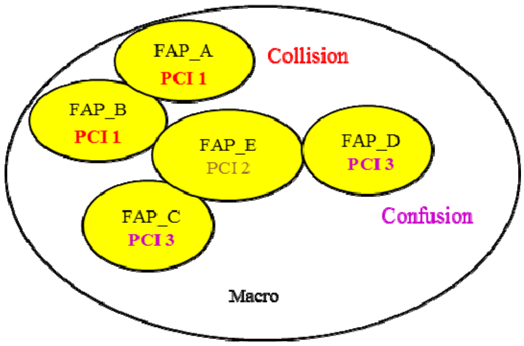


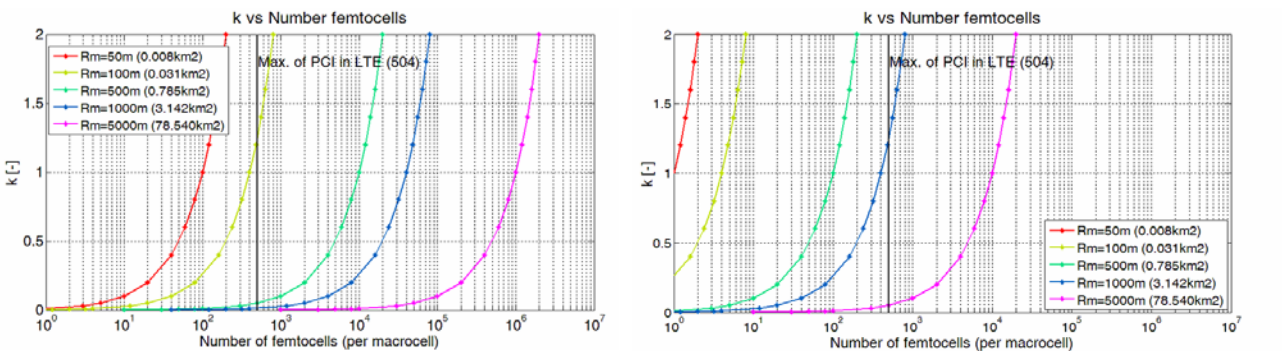
Figure 48. Example of collision and confusion scenarios

4.4.1 Analysis

The Figure 49 provides number of femtocells per macrocell for different size of macrocells radii (denoted as Rm in the figures) and parameter *k*. The parameter *k* is given as

$$k = \frac{\sum_i S_i^{Femto}}{S^{Macro}} \tag{40}$$

where parameter S^{Macro} denotes the overall macrocell area and parameter S_i^{Femto} area of *i-th* femtocell. The parameter *k* represents an overlap of femtocells. For example, *k* = 2 means two fully overlap femtocells, i.e., two femtocells is placed one above the other (e.g., 2-storey buildings). The figure also highlights a threshold indicating the max. number of available PCIs in the LTE network. Figure 50 shows number of femtocell per 1km^2 macrocell area when considering a different size of femtocells radii.



a) R_{FAP} = 5 m b) R_{FAP} = 50 m

Figure 49: Number of femtocells for various macrocells radii Rm, R_{FAP} = 5m

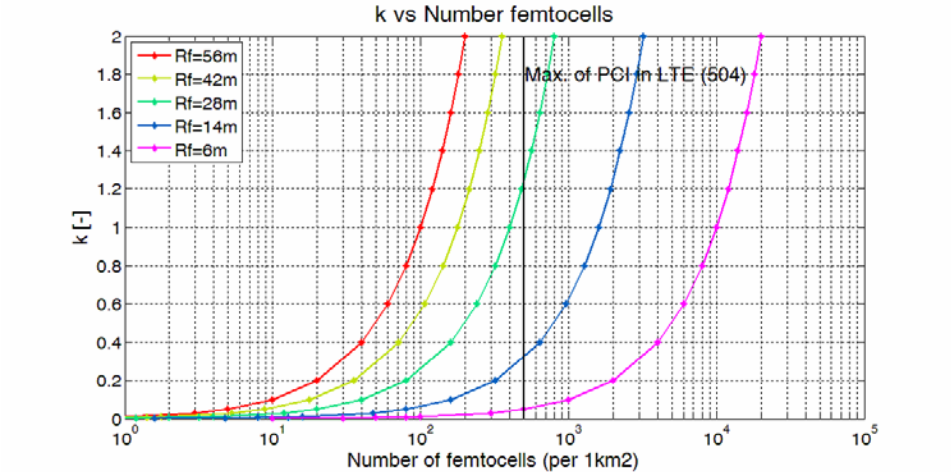


Figure 50: Number of femtocells per 1km^2 for various femtocell radii Rf, R_{MBS} = 564m

To ensure the confusion-free allocation of PCIs, a newly introduce FAP has to be assigned a PCI that differs to the PCIs of direct neighbors FAPs, i.e., FAPs placed at the 1st ring level (see Figure 51).

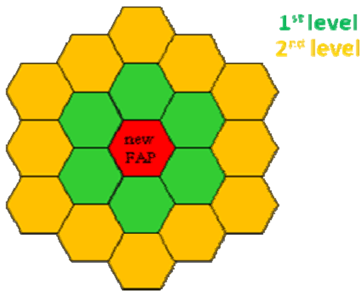


Figure 51. Levels of neighbouring cells

In case of equally distributed FAPs, the max number of neighbouring FAPs per a FAP ensuring collision and confusion-free scenario, called N_n, can be found as:

$$N_n = \sqrt{N_{PCI}} - 1 \quad (41)$$

where N_{PCI} represents number of available PCIs. Figure 52 illustrates values of N_n for different number of PCIs. In case of LTE, the N_{PCI} =504 and N_n equals to 22.

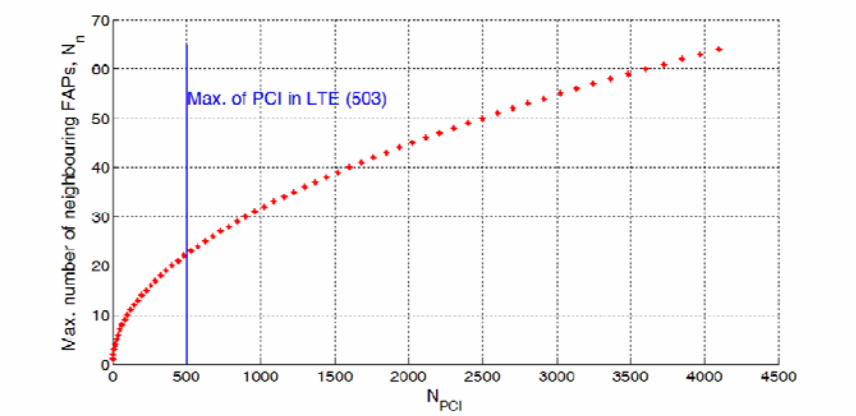


Figure 52. Number of collision-free neighboring FAP for different value of PCI available

In other words, if any FAP borders with less then 23 cells, there can be still provided the collision and confusion free scenario at the femto cell level. To ensure a macro-femto collision free scenario, PCIs assigned to FAPs should differ to PCIs assigned to MBS. A FAP can find out the macro PCI either by directly detecting the MBS signal or by learning macro PCI form the neighbouring FAPs.

Figure 53 shows the required time to discover of PCIs of neighboring FAPs when considering different levels of neighboring FAPs and different processing time (T_{proces}); a decentralized allocation method using radio environment scanning is considered. The newly introduced FAP scans environment to discover PCIs used by direct neighbors (FAPs at 1st ring level), then direct neighbors of neighbors (FAPs at 2nd ring level), then PCIs of FAPs at 3rd ring level, etc. The T_{proces} is composed of three components: i) time to send a request to a direct neighboring FAP, ii) time to process the request by the FAP, and iii) time to send the answer to the neighboring requesting FAP.

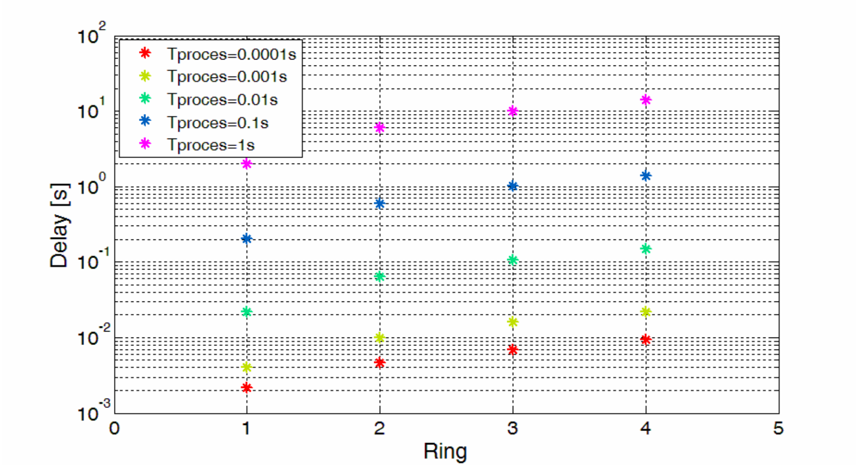


Figure 53. Required time to discover of used PCIs for different levels of neighboring FAPs and different FAP processing time (T_{proces})

As mention before, to provide a collision-free scenario, a new FAP needs to know PCIs of direct neighbours (FAPs at 1st ring level). To ensure also a confusion-free scenario, a new FAP needs to learn at least PCIs of neighbors of direct neighbors (FAPs at 2nd ring level). Notice that the knowledge of PCIs at the 2nd ring can prevent confusions at the femto cell level but not at the macro cell level. From the MBS view, there can still be two or more FAPs having the same PCIs under its coverage that would lead to the confusion scenario at the macro cell level. Knowledge of PCIs beyond the 2nd ring level (i.e.. ring 3, 4, etc.) enables to allocate PCIs more uniformly in the macro cell; the FAP knows large surrounding area. Additionally, in case of small macro cells, the new FAP can learn this way PCIs of theoretically all FAPs of the given macro cell and the confusion event at the macro cell level can be avoided.

4.4.2 FAP clusters

As it was mention in the previous section, due to limited number of available PCIs, there is not always possible to guarantee confusion-free condition in a dense urban deployment scenario such as deployment of a lot FAPs under one MBS. One solution how to deal with this problem is to introduce FAP cluster notation where a FAP cluster represents a set of several neighboring FAPs (Figure 54).

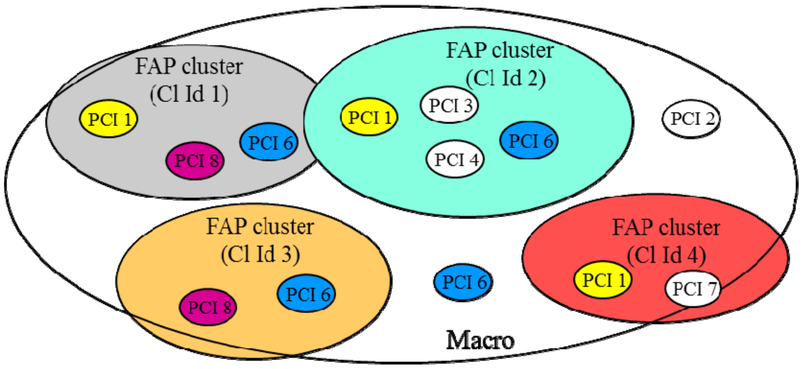


Figure 54. FAP cluster concept

In the FAP cluster concept, a macrocell is composed of none, one, or several FAP clusters where each cluster is assigned a unique *FAP cluster Id* (called *Cl Id*). A FAP cluster itself is composed of several FAPs and a FAP is assigned, if possible, a unique PCI in the cluster (called $PCI_{cluster}$ *Id*). The same $PCI_{cluster}$ *Id* can be repeated in other FAP clusters (in Figure 54, see for example PCI = 1). Thus, a whole PCI of FAP is composed of *Cl Id* and $PCI_{cluster}$ *Id* can be written as:

$$PCI\ Id = Cl\ Id + PCI_{cluster}\ Id \tag{42}$$

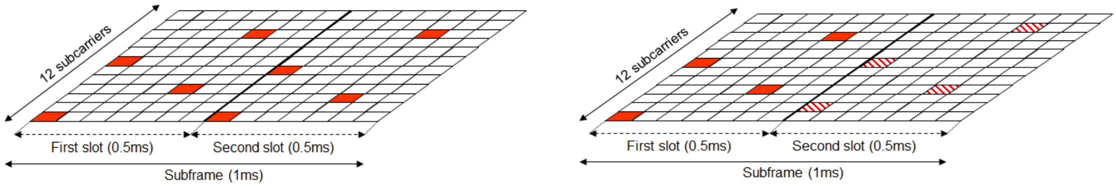
The number of clusters (i.e., *Cl Id*) can vary from macrocell to macrocell; based on density of FAPs in a given macrocell. Additionally, the *Cl Id* value can be updated on the fly as the number of FAPs in the macrocell gradually increases. A MBS knows the number of clusters in its cell and the number is sent over the broadcast channel of MBS and FAPs. The FAPs learn about the number of clusters either via the BCH of MBS/FAPs or via the backbone. The assignment method of $PCI_{cluster}$ *Id* within a FAP cluster is independent of PCIs assignment methods in the other FAP clusters; different algorithms can be applied in different FAP clusters (e.g., see section 2.4.).

A FAP that is located outside of a cluster, i.e., a FAP cannot hear any neighboring FAPs (e.g., FAP PCI = 2 in Figure 54) can occur. All such isolated FAPs per macrocell are assigned the same specific predefined FAP cluster identifier ($Cl\ Id_{isolated}$), e.g., *Cl Id* = 0. As other FAPs, isolated FAPs learn about the value of $Cl\ Id_{isolated}$ either via the BCH of MBS or via the backbone.

The FAP cluster concept can be introduced using two approaches:

a) In the first approach, the identifier *Cl Id* could be specified as a newly introduced identifier that is added to the current PCI. Thus, the number of available PCIs would increase and could be flexibly adapted as the number of active FAPs increases. For example by creating 8 FAP clusters, the PCI range can rise up to 4096. In this case, by knowing the PCIs of FAPs at the 1st and 2nd ring, the number of neighbouring FAPs per a FAP, ensuring the collision and confusion free scenario (at the femto cell level), would increase from 22 ($PCI\ Id_{MAX}=504$) up 64 ($PCI\ Id_{MAX}=4096$), see Figure 52.

   On the other hand, this approach would require updating the corresponding 3GPP specifications. When considering the LTE system, the proposal can be implemented as follow. In LTE, a PCI is represented by Primary and Secondary Synchronization Signals (PSS, SSS) that are repeatedly transmitted by specific subcarriers and OFDM symbols (Figure 55a); the PSS and SSS are carried in exactly specified subframes. Different PCIs means different combinations of subcarriers-OFDM symbols. For a given PCI, the same subcarriers-OFDM symbol combination is repeated in the subframe two times, i.e., the same combination is used in both slots. Instead of repeating the same combination in both slots, we propose to use in the second slot either partially or entirely a different subcarriers-OFDM symbol combination (see Figure 55b). This solution would enable increasing the number of PCIs up to 254 thousands (i.e., 504x504).



a) Current implementation   b) Proposed implementation

Figure 55. Implementation of PCI in the LTE technology

b) In the second approach, the identifier *Cl Id* could be specified as sub-identifier of the currently used PCI. This can be done very easily by reserving certain PCIs to FAP clusters. However, the number of available PCIs would remain a limiting factor, i.e. occurrence of confusion events would remain issue.

It might happen that the PCI assignment cannot be always done in the confusion-free manner and the same PCI(s) has to be reused within a FAP cluster. This is mainly problem in case of handover and paging procedures where the cell identifier is employed. In case of handover, the MBS cannot unambiguously decide to which FAP the connection should be passed on. A solution could be instead of sending just the PCI of target FAP, the UE would also send a list of neighboring PCIs of the target FAP. The target PCI together with the neighboring list of PCI(s) creates an *extended* (*virtual*) FAP PCI that can be used by MBS to correctly deduce the target FAP and thus where the connection should be handed on. If the neighboring PCI list is not available (neighboring FAPs do not exist or the UE can hear none), the target FAP cannot be unambiguously identified and the handover is not executed; the UE remains connecting to the MBS. Similarly, the extended virtual FAP PCI can be also used during the paging procedure to determine where to send the paging message to find out the searching UE.

4.5 Authorization procedure

This section is divided into two subsections. Firstly, an access and authorization of so called visiting users to the CSG FAP is analyzed and new procedure for simple management of this access is presented. Secondly, the authorization in case of user's emergency is investigated in this section.

4.5.1 Access of visiting users to closed FAP

This section addresses the dynamic management of CSG list of UEs with enabled access to the closed FAP (denoted as CSG FAP). The goal is to ensure easy and manageable “adding” or “removing” new UEs, so called "Visiting UEs", to the CSG list. The reference scenario is depicted in Figure 56. In this figure, users with access to the CSG FAP are denoted as CSG UEs. If a visiting UE (V-UE) moves so close to the CSG FAP that it is able to receive identity of this cell, it also receives information about CSG status. It means, the V-UE is able to determine whether this FAP utilize closed or open access. This is indicated by *CSG indication* flag set to "*true*" broadcasted by each FAP together with other information (see [3GPP TS 36.304]). Each UE is aware of CSG FAPs that this UE can access. These CSG FAPs are included in EU's *CSG whitelist*. The whitelist is a combination of *Allowed CSG list* and *Operator CSG list*. The former one is under control of both operator and user, while the latter one is under exclusive control of the operator (for more information, see [Qualcomm10]). Both lists should be stored in UE's USIM (Universal Subscriber Identity Modul). Each UE can access all CSG FAPs included at least in one of those lists. Therefore, if the CSG FAP in UE's range is listed in whitelist, conventional procedures for connection control, defined in [3GPP TS 36.331], are performed. In this section, we focus on the scenario, when the CSG FAP is not included in the UE's whitelist, but the UE still would like to access this FAP. In this case, this UE must obtain permission from a subscriber of the CSG FAP.

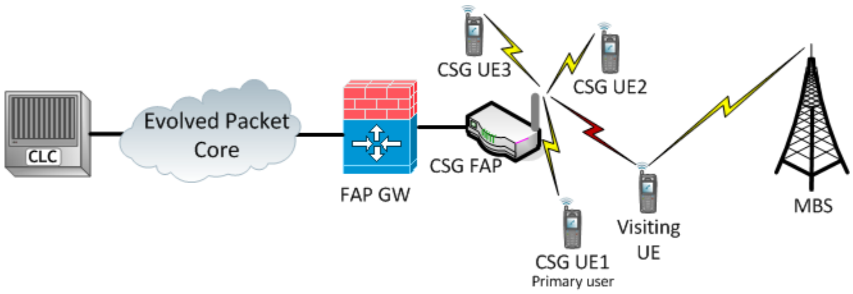


Figure 56. Reference scenario for management of visiting users

4.5.1.1 Detection of CSG FAP by UE

The UE is able to detect CSG FAP by decoding its synchronization signals and its status (closed, open, or hybrid). However, if the UE would like to perform handover to this cell, it should perform measurement of signal level received from this CSG FAP. The handover can be performed even if no measurements are reported to the network. However, this introduces risk of UE's disconnection if the CSG FAP signal is weak comparing to signal of neighboring stations. Therefore, even if the measurement is optional, it is recommended to perform it before handover. Current 3GPP standards imply exclusion of CSG FAP from signal measurement and reporting if no CSG FAP is in the UE's whitelist (see [3GPP TS 36.304] and [3GPP TS 36.133]). Therefore, a modification enabling UE to measure and to report signal to the networks even if the CSG is not included in its whitelist is necessary. The inclusion of such a CSG FAP in measurement and reporting can be done in following way. If the V-UE enters the cell of CSG FAP, which is not in its whitelist (no other CSG FAP is included as well) however the V-UE would like to attach to this CSG FAP, the visiting user must manually enable measurement of this cell. The user temporarily enables to measure and report all CSG FAPs in its neighborhood. For the network purposes, this is indicated by setting of *MeasCSGFlag* flag in whitelist. The *MeasCSGFlag* is new flag kept in UE's USIM along with whitelist.

A timer for this measurement and reporting must be defined to avoid useless network overloading with redundant reporting of the cells if the visiting user forgot to turn off this measurement reporting. Prior to the time expiration, V-UE must obtain permission from a CSG FAP subscriber. By CSG FAP subscriber is understood a user with the CSG FAP in its whitelist, which has permission to enable/disable access to V-UEs. In the simplest way, the user who is operator's signed subscriber (denoted as Primary subscriber) should be the user in charge of CSG list management. Besides a list of potential users with permission to control the CSG list of enabled UEs should be defined if the Primary subscriber is out of the CSG FAP range or if the Primary user permits such rights to other members of CSG (e.g., other members of family).

4.5.1.2 Management procedure enabling access of V-UEs

The general principle of granting the V-UE with access to the CSG FAP is depicted in Figure 57. Note that for the sake of simplicity, the FAP and the operator's network (including the MBS) are represented as one entity in this figure since all communication between both is via backbone. More details on backbone communication are presented later in this section. If a V-UE detects a CSG FAP, it can try to enter this FAP. In conventional way, the UE's attempt for entering the CSG FAP without permission would be rejected as both the FAP and the network consider this request as unjustified. Therefore, the request from the V-EU must contain new flag, "*Not Allowed*". This flag indicates that the V-UE is aware of the fact that it cannot access this CSG FAP, and it applies only for "V-UE permission".

After that, the network in cooperation with the FAP selects the appropriate user having permission to accept or deny the V-UE request (denoted as Look up CSG members in figure). The selection is done only among CSG users with permission to grant a temporary access. Among those UEs, the one with highest priority out of all CSG UEs in FAP's range is chosen. This selected UE (i.e., Primary CSG UE in Figure 57) is asked if the V-UE can be admitted to the CSG FAP. The Primary CSG UE then either acknowledge or reject this request. If the access of V-UE is accepted, the Primary CSG UE must define authorization details and *Class of V-UE*. By authorization details is meant definition of password for verification of the V-UE. By setting *Class of V-EU*, the primary CSG UE can define limitations for V-UE (e.g., a limit on bandwidth, overall amount of transferred data by V-UE, restriction of some applications or services, duration of the access, etc.).

The restrictions set by the Primary CSG UE are then negotiated with the V-UE. Also, the V-UE is asked to verify its identity by password. The handover to the CSG FAP can be initiated only if the password provided by the V-UE matches the one provided by Primary CSG UE and if the V-UE accepts all restrictions set by the Primary SCG UE.

Two options of management are considered in this section: In-Band (IB) and Out-Of-Band (OBB). The first one assumes management communication (for handling V-UE entry for CSG FAP) within conventional band used by the UE for all communications with the network. The second one requires other radio technology, such as Bluetooth, for the management communication.

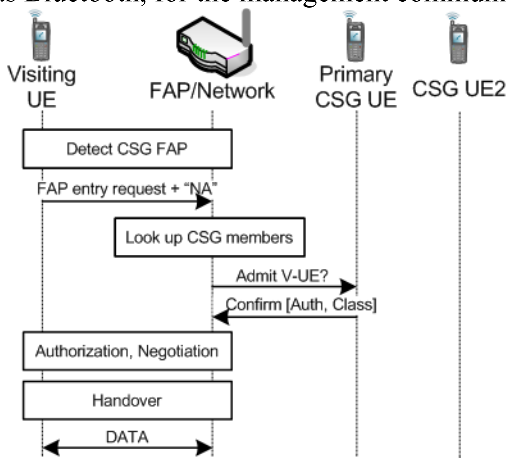


Figure 57. Flow chart of V-UE entering the CSG FAP

In Figure 58, the detailed procedure enabling the V-UE to enter the CSG FAP with utilization of IB is depicted. Both signaling over radio channel and over backbone link, occurring between networks and the CSG FAP, is illustrated. If the V-UE is able to detect the CSG FAP, it sends request for access this FAP. The request is transmitted to the current serving MBS since communication with the FAP is not established. If the "*Not Allowed*" access is indicated by the V-UE, the MBS forwards the request to the CSG FAP via backbone. The FAP then conveys the *V-UE Request* message to the Primary CSG UE. This message contains only identification of the V-UE (IMSI and Name) to minimize redundant signaling overhead.

The Primary CSG UE can either grant or deny the request in *V-UE Response* message. This message must contain ACK or NACK indications (grant or deny). If ACK is present, then the Primary CSG UE can define additional requirements or limiting conditions for using the CSG FAP (*Class of V-UE*). Moreover, a password for verification of the V-UE must be included in this message. This message is further delivered to the V-UE through the FAP, the FAP's backbone, and the serving MBS. The V-UE enters either password with acknowledgment of requirements set by the Primary CSG UE or rejection of the requirements specified in *Class of V-UE*. This data is delivered to the CSG FAP via the serving MBS in *V-UE Info* message. The CSG FAP then compares both passwords. If both passwords are identical, the FAP confirms admission of the V-UE to the Primary CSG UE and the network by means of *V-UE Confirm* message. Based on this message, the network includes the V-UE in the list of UEs with access to this FAP and handover is initiated.

In the network, a CLC (CSG List Control) element is responsible for management and control records related to all CSG lists. This block is composed of several entities. More details on architecture of individual CSG list management entities can be found in [Qualcomm10]. Since the temporary agreement on enabling the V-UE to the CSG FAP does not imply any further commitments to enable the access in the future, no update of V-UE whitelist is required. In addition, all new records must be deleted after an expiration of the access grant. Therefore, a timer must be run in the CSG FAP to ensure deletion of such records. The update of whitelist is necessary only if the Primary CSG UE indicates unlimited access grant for the V-UE (note that this is not indicated in Figure 58 since we assume only temporary access).

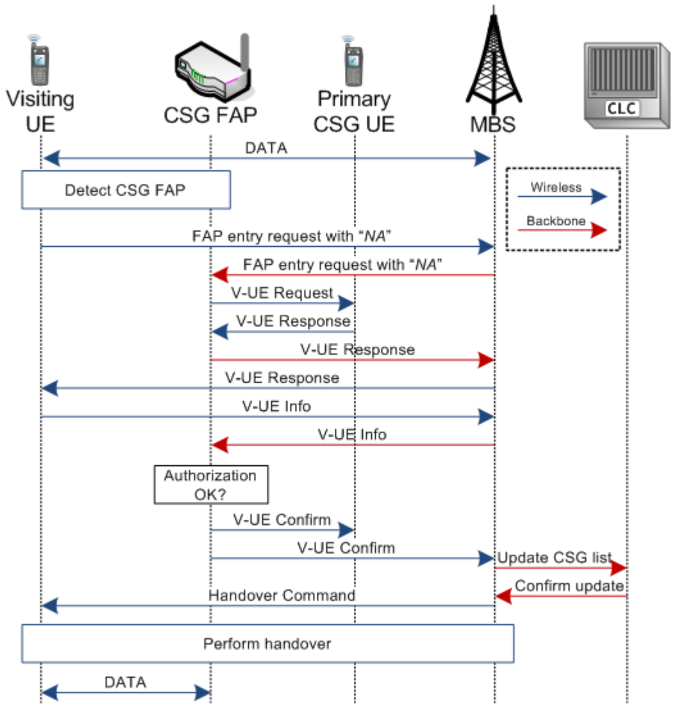


Figure 58. Visiting UE enter to CSG FAP using IB wireless and backbone

Another option of managing visiting user access is to use OOB communication since nearly all current devices are equipped with short-range communication technology such as Bluetooth. If a V-UE comes to close vicinity of a CSG FAP and if a Primary UE is in range of OOB communication technology, the V-UE can initiate procedure via OOB by transmission of *V-UE Request*. This message is sent via OOB directly to the Primary UE and it contains only identification of the V-UE. The Primary CSG UE can either accept or reject the V-UE by *V-UE Response*. In case of accepting the V-UE request, password and additional limitations can be set by Primary CSG UE in the same way as in case of IB method. The confirmation of those requirements is sent by V-UE together with password in *V-UE Info*. If the OOB is used, the Primary CSG UE is responsible for evaluation of the authorization. Once the V-UE agrees the conditions defined by the Primary CSG UE and both password match, the final acknowledgment is sent to V-UE in *V-UE Confirm*. At the same time, the Primary CSG UE informs CSG FAP about temporary inclusion of the V-UE to the list of UEs with enabled access. The CSG

FAP forwards this information to the CLC. Also, the handover is initiated by the serving MBS after reception of *V-UE Confirm* by the MBS from the CSG FAP.

Comparing both approaches (IB and OOB), the later one requires enabled OOB communication technology on both V-UE and selected CSG UE. The OOB could negatively influence battery lifetime of both involved UEs (V-UE and Primary CSG UE) due to need of other radio communication technology. However, the OOB communication is required only for a very short time at the beginning of the procedure. Thus, only negligible impact on UE's battery lifetime is assumed. On the other hand, involvement of only a CSG UE is assumed during authorization of V-UE and negotiation of Class of V-UE is required by OOB. Therefore, it impose lower amount of overhead on radio as well as backbone links. Therefore, the OOB way is more profitable if both UEs are equipped with this technology.

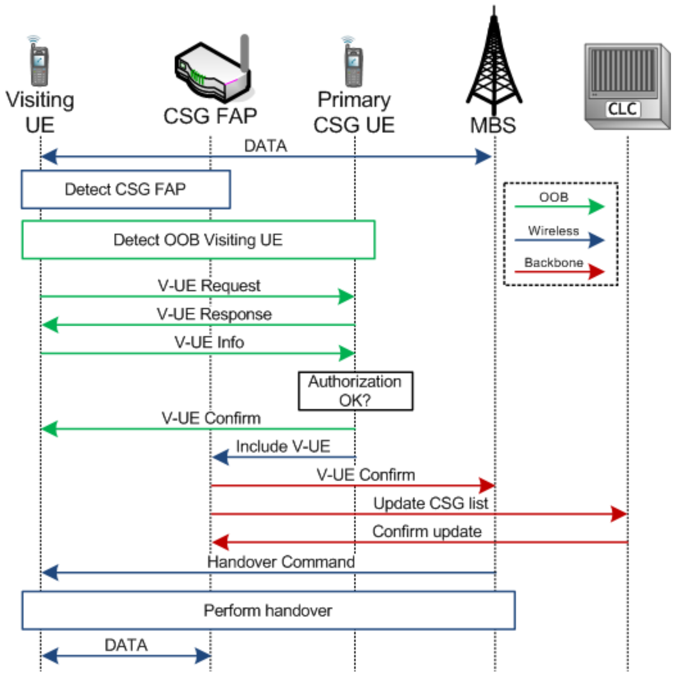


Figure 59. Visiting UE enter to CSG FAP using OOB communication

4.5.1.3 Management messages for visitor access

In this section, summarization of new management messages and their content are presented. For both approaches of handling V-UE access, four new messages must be designed: *V-UE Request*, *V-UE Response*, *V-UE Info*, and *V-UE Confirm*. Each message starts with message ID to distinguish individual messages.

The *V-UE Request* message contains only IMSI (International Mobile Subscriber Identity) and a name of the V-UE. The name is assigned by the user. To avoid useless overloading of backbone, it is limited to 16 characters (each character is 8 bits). The *V-UE Request* message is presented in Table 10.

Message field	Size	Description
Message ID	TBD	Identification of the message
ID of V-UE	64 bits	Identification of the UE by IMSI
UE's name	up to 128 bits	Name assigned by visiting user to its V-UE

Table 10. Structure of V-UE Request message

The second message, *V-UE Response*, is presented in Table 11. This message mandatory contains identification of the V-UE in the same way as in *V-UE Request*. Further, if access is accepted (i.e., ACK is included in the second field), the password must be contained. The length of password field depends on encrypting algorithm and on the password length. The password can be followed by optional conditions, restrictions, and duration of the V-UE access. The length of this field is variable and depends on the amount of restrictions.

Next, *V-UE Info* message is presented in Table 12. This message is a reply of the V-UE to *V-UE Response*. The mandatory fields of the *V-UE Info* are *ID of V-UE* and *ACK/NACK* of V-UE Class defined by the primary CSG UE. The later one indicates whether the V-UE accepts the condition for the FAP's access defined by the primary CSG UE. If the conditions are accepted, the field with password must be included just after the ACK/NACK field for the purpose of access verification.

Message field	Size	Description
Message ID	TBD	Identification of the message
ID of V-UE	64 bits	Identification of the UE by IMSI
ACK/NACK	1 bit	ACK ... access of the V-UE enabled NACK ... access of the V-UE disabled
Password	Variable	Password for verification of the V-UE
Class of V-UE	*Variable*	*Defines restriction to the V-UE and duration of granted access*

Table 11. Structure of V-UE Response message

Message field	Size	Description
Message ID	TBD	Identification of the message
ID of V-UE	64 bits	Identification of the UE by IMSI
ACK/NACK	1 bit	ACK ... acceptation of *Class of UE* NACK ... rejection of *Class of UE*
Password	Variable	Password for verification of V-UE's

Table 12. Structure of V-UE Info message

The last message, *V-UE Confirm*, is presented in Table 13. This message ends the process of granting the V-UE's access to the CSG FAP. The mandatory field with UE's ID is included to easy identify the UE by the MBS and the network. Further, 9 bits FAPs ID is included. We suppose to use the same indicator as Physical Cell ID (PCI). The PCI distinguishes up to 504 cells [3GPP TS 36.300], thus 9 bits are required for identification. Last, information on duration of the access to the CSG FAP is included. This information must be delivered to network to ensure deletion of the new record in CSG list in CLC after expiration of the access grant. For indication permanent access, this field should be set to zero.

Message field	Size	Description
Message ID	TBD	Identification of the message
ID of V-UE	64 bits	Identification of the UE by IMSI
CSG FAP ID	9 bits	Identification of the FAP, the same number as the FAP's Physical Cell ID can be used.
Access grant duration	TBD	Information on duration of enabled access to the CSG FAP. If this field equals to zero, unlimited access is indicated.

Table 13. Structure of V-UE Confirm message

4.5.1.4 Business and legal aspects of the proposed procedure

The V-UE access can be free of any charges to CSG FAP subscriber. In this case, all additional costs (if there are any) are charged to the CSG FAP subscriber. However, the access can be considered as paid (e.g., in case of longer duration of the V-UE's stay, for example, in hotel). In this case, the way of charging must be defined. The possible option is to reduce the CSG UE month fee (e.g., for a ratio of data transferred by the V-UE, or for fixed fee per time). The V-UE's bill must be increased for the same amount.

Besides, aspects related to legal or ethical issues must be considered. Therefore, it must be ensured that the information on fact that the V-UE accessed the CSG FAP will be stored in networks for a certain period (defined by laws of individual countries).

The FAP must be able to monitor amount and statistics (e.g., daytime of the V-UE activity) of traffic transferred by the V-UE. These statistics should be open for CSG UE if this was agreed during negotiation of the *Class of V-UE*. On the other hand, access of all CSG UEs to the content of the V-UE traffic must be strictly prohibited.

4.5.1.5 Conclusions

This section defines new procedure to enable easy access of visiting users to the CSG FAPs. The proposed procedure defines chart flow of management messages as well as their content. Two approaches enabling access of the V-UE to the CSG FAP are proposed. The first, in-band, assumes only communication via operators radio and backbone links. All management messages transmitted by the V-UE before obtaining access to the CSG FAP are received by the serving MBS and then forwarded to the CSG FAP via backbone. The second one, out-of-band, exploits other radio interface such as Bluetooth. The OOB offloads negotiation of the V-UE access to the CSG FAP from in-band radio and backbone to Bluetooth. Hence, the OOB approach is more profitable if both involved UEs (V-UE and Primary CSG UE) are quipped with Bluetooth.

4.5.2 Emergency calls

This subsection assumes only CSG FAP's. A UE shall be connected into the cell with highest level of signal (RSSI, CINR, etc.) including FAPs in the case of emergency calls. The CSG prevents from knowledge of all near cells, UE knows only limited number of them, i.e., in this state the UE has no access to CSG cells. Therefore, a CSG whitelist, shall be updated.

In the case of emergency call is in progress, it is assumed backbone handle the communication between FAP's.

The CSG whitelist is updated by System information acquisition procedure as addressed in [3GPP TS 36.331 V 10.3.0].

If emergency calls are initiated, it is included in messages of RRC establishment procedure, i.e. in *RRCConnectionRequest* message in the field *EstablishmentCause*. Based on this message the network knows emergency call is initiated. However, it does not include solution for emergency calls initiation from CSG cells, which are not included in CSG whitelist.

4.5.2.1 Proposal 1

The proposal 1 includes modified RRC establishment procedure, System information acquisition procedure and handover procedure. The proposed message exchange is depicted in Figure 60.

1. *RRCConnectionRequest* message is sent by the UE. It includes *EstablishmentCause field* with the "value" emergency. The UE informs the network about emergency call initiating.
2. In this step the UE is not connected to CSG cell at first. It is necessary to change CSG membership by network. This requirement is described in [3GPP TS 22.220]. It also presents

temporary member and its granted access rights for limited period of time, unlimited membership or time period for emergency calls.

3. Network initiates System information acquisition procedure to modify CSG whitelist. Now, the UE knows new cells in the range including CSG cells.
4. Handover procedure "CSG and Hybrid Cell Handover" is described in [3GPP TS 25.367]. Now, the UE can camp on the cell including CSG cells.
5. Finish the RRC establishment procedure by *RRCConnectionSetup and RRCConnectionSetupComplete* messages. Now, the UE sends unicast data.

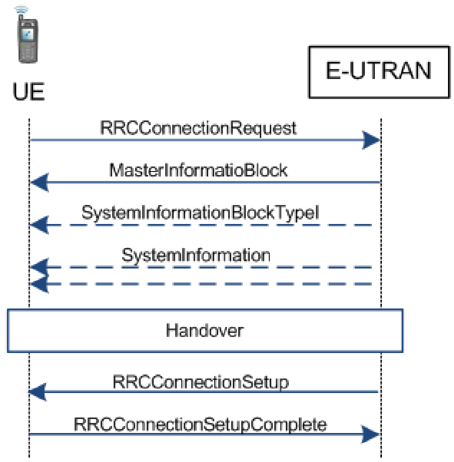


Figure 60. Proposal 1 of emergency call for femtocells

The proposal describes a new procedure, which is compound from messages of present RRC establishment procedure, System information acquisition procedure and handover procedure. The procedure starts with the initiation of emergency calls. This information is included in *RRCConnectionRequest* message. Then the network shall change CSG membership of specific UE. System information acquisition procedure is consequently performed. The CSG whitelist is now changed. Handover procedure follows; the UE can camp on any cells in the range. Two remaining messages of RRC establishment procedure are sent. Then, the UE is switched from RRC_idle to RRC_connected state and can transfer unicast data.

4.5.2.2 Proposal 2

The proposal 2 differs from the proposal 1 in number of messages of System information acquisition procedure. It is not necessary to perform all messages of this procedure. The UE shall be only informed about change in CSG membership. It includes *SystemInformationBlockType1*. In addition, this whole procedure is performed after every handover. The proposed message exchange is depicted in Figure 61.

1. *RRCConnectionRequest* message is sent by the UE. It includes *EstablishmentCause field* with the "value" emergency. The UE informs the network about emergency call initiating.
2. In this step the UE is not connected to CSG cell at first. It is necessary to change CSG membership by network. This requirement is described in [3GPP TS 22.220]. It also presents temporary member and his granted access rights for limited period of time, unlimited membership or time period for emergency calls.
3. Network sens *SystemInformationBlockType1* message to inform the UE about CSG membership. Now, the UE knows new cells in the range including CSG cells.

4. Handover procedure "CSG and Hybrid Cell Handover" is described in [3GPP TS 25.367]. Now, th UE can camp on the cell including CSG cells.
5. Finish the RRC establishment procedure by *RRCConnectionSetup and RRCConnectionSetupComplete* messages. Now, the UE transfers unicast data.

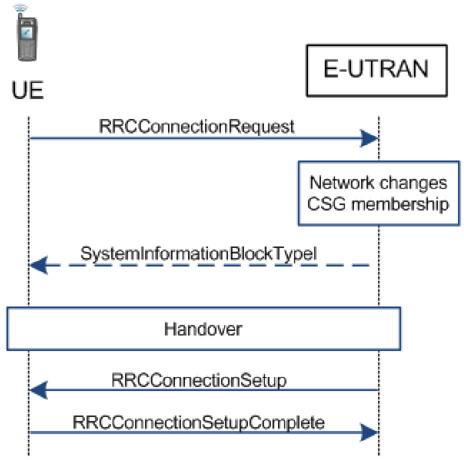


Figure 61. Proposal 2 of emergency call for femtocells

Disadvantage of the proposal 1 is performance of all System information acquisition procedure. This disadvantage is eliminated in the proposal 2, which includes only necessary information about change of CSG membership in *SystemInformationBlockType1* message.

However, the proposal 2 transfers only necessary information about CSG IDs, it does not include all system information messages, *SystemInformationBlockType2* - *SystemInformationBlockType10*. For example *SystemInformationBlockType9* contains information about HNB Name.

4.6 Control procedures for FREEDOM environment in coordination algorithms based on the exchange of interference pricing

Some of the algorithms investigated in activity 3A2 (D3.2) deal with the coordination of several terminals by exchanging information at control-plane level for decentralized radio resource allocation. More specifically, a coordinated mechanism was proposed to design the precoders that maximize the weighted sum-rate within a set of femtocells or that minimize the total transmit power while guaranteeing a minimum bit rate per user. MISO and SISO cases were particular solutions of the proposed approach. Also, a simpler and better LTE adapted algorithm was derived in WP3 for MBS-FAPs interference coordination.

Unlike more conventional approaches, where FAPs act as selfish agents competing for the resources available at the expenses of injecting undue interference to the whole system, WP3 algorithms assume that FAPs can exchange control information to compute the so called interference prices that reflect the compensation to be paid for the interference generated to users connected to other FAPs. The goal of this section is to design and specify the control procedures to implement WP3 techniques as well as to evaluate the benefit from coordination among femtocells and macrocell. Unlike 3D2 the degradation due to pricing quantization is evaluated here. The assumptions and scenarios are the same as described in D3.2 (see [FRED3.2] for more detail).

4.6.1 Coordinated precoding based on pricing

As described in WP3, to design the precoders of different FAPs in a coordinated way, the following steps need to be taken:

1. Each FUE detects the E-UTRAN cell global identifier (ECGI) of surrounding FAPs and measures channel state information (CSI) on each physical resource block (PRB) (or minimal resource allocation unit) for the serving FAP and dominant interferers. A neighbor FAP is considered a dominant interferer if the average signal strength received from this FAP with respect to the average signal strength received from the serving FAP is above a given threshold. The FUE also estimates how the total interference affects the quality of the communication (interference sensitivity). This information must be reported to the serving FAP.

2. The FAP that the FUE is connected to signals a DL-cost message to the dominant interfering FAPs. This message consists of the ECGI of the sending FAP and the identifier of the interfering FAP (receiving FAP), and a field/s indicating the interference cost for each PRB due to the transmission of the FAP for which the message is meant.

3. The FAP receiving a DL pricing message or messages from neighboring FAPs computes a global price per PRB. WP3 algorithms allocate power on each PRB according to the price associated for the PRB. In the SISO case this results in lower power allocation at those PRBs with greater prices. In the MISO and MIMO case, the transmitting FAP will avoid allocating large power at those carriers and **directions** with greater price.

Table 14 summarizes the control information to be exchanged to support the computation of the optimal precoders in order to support WP3 algorithms. The contents of the table are detailed in next subsections.

Control information to be exchanged	Direction	Interface
Each FUE collects and reports CSI regarding the link with the serving FAP	From FUE to serving FAP	LTE Uu
Each FUE collects and reports CSI regarding the link with dominant interfering FAPs	From FUE to serving FAP	LTE Uu
Each FUE estimates and reports how the total interference affects the quality of the communication (interference sensitivity)	From FUE to serving FAP	LTE Uu
From the information received from FUEs, each FAP computes and sends a DL-cost per PRB to each member of a list of dominant interfering FAPs	From each FAP to dominant interfering FAPs	To be defined (possibly X2)

Table 14. Control information to be exchanged in WP3 algorithms based on pricing

4.6.1.1 FUE procedures

Interface between FUEs and FAP

The transmission of control information between FUEs and FAP should be part of the Radio Resource control protocol, RRC, in the radio interface. The LTE Uu (radio interface of LTE), documented in TS 36.2xx, and TS 36.3xx, includes three mechanisms:

- **Control signaling**: broadcast information including specific information of the access network known as access stratum, and also information of the backbone known as non access stratum.

- **Transmission of IP packets** through radio bearers designed specifically for IP traffic.

- **Transmission of control information between UE and eNB** known as Radio Resource Control protocol, RRC. The RRC protocol includes mechanism for the control and transmission of radio measurements from UEs to eNB, handover, and the establishment, modification and release of radio bearers.

FUE procedure for detecting and reporting Channel State Information (CSI) in the link FUE-serving FAP

The precoder design requires the knowledge at each PRB (or minimal resource allocation unit) of the channel and the noise plus interference covariance matrix in the link FUE-serving FAP. This information is required in order to compute, for each PRB, the matrix $\mathbf{H}_{ff}^{c\,H}\left(\mathbf{R}_f^c\right)^{-1}\mathbf{H}_{ff}^c$, where $\mathbf{H}_{ff}^c$ stands for the $N\times M$ MIMO channel matrix, including the path-loss and the random channel amplitude, between the FUE and the serving FAP normalized with respect to the noise power at the c-th PRB, and $\mathbf{R}_f^c$ denotes the noise plus interference covariance matrix normalized with respect to the noise power at the same PRB. This matrix is necessary for the precoders design even in the absence of coordination among femtocells.

A way to feedback the matrix $\mathbf{H}_{ff}^{c\,H}\left(\mathbf{R}_f^c\right)^{-1}\mathbf{H}_{ff}^c$ is transmitting the matrix eigenvectors by means of Channel Vector Quantization along with an indicator for the Signal-to-Interference plus Noise Ratio (SINR) for each channel eigenmode. This procedure or even this level of granularity for the channel reporting is, however, very far from what is currently considered in LTE standard.

FUE procedure for reporting interference sensitivity and the channel in the link FUE-neighbor FAP

An important parameter in WP3 algorithms is the so called interference sensitivity matrix (in general for the MIMO case), which boils down to a scalar value for the SISO and MISO cases. This parameter measures the sensitivity of the rate that can be used at a given PRB with respect to the noise and total interference. Assuming that Shannon capacity is used as the function to obtain this rate, the interference sensitivity depends on the noise plus interference covariance matrix $\mathbf{R}_f^c$ and the desired signal spatial covariance matrix $\mathbf{X}_f^c = \mathbf{H}_{ff}^c\mathbf{S}_f^c\mathbf{H}_{ff}^{c\,H}$

$$\mathbf{\Pi}_f^c = -\left(\frac{\partial}{\partial \mathbf{R}_f^c}\log_2\left|\mathbf{I}_N + \mathbf{H}_{ff}^c\mathbf{S}_f^c\mathbf{H}_{ff}^{c\,H}\left(\mathbf{R}_f^c\right)^{-1}\right|\right)^T = \log_2 e\,\left(\mathbf{R}_f^c\right)^{-1}\left(\mathbf{I}_N + \mathbf{X}_f^c\left(\mathbf{R}_f^c\right)^{-1}\right)^{-1}\mathbf{X}_f^c\left(\mathbf{R}_f^c\right)^{-1} \tag{43}$$

which for the SISO and MISO cases boils down to the following scalar value:

$$\pi_f^c = \frac{1}{1+\frac{1}{SNIR_f^c}}\frac{1}{\left(1+I_f^c\right)} \tag{44}$$

which is always positive and smaller than 1.

In order to compute the interference prices, required for the coordinated precoders design, the receiver needs to provide the information regarding interference sensitivity at each PRB. The FUE needs to estimate and provide the channel between the FUE and each dominant interferer (cross-channel) at each PRB as well. This procedure is not considered at all in LTE standard.

4.6.1.2 FAPs procedure

Interface between FAPs

Despite there is no interface defined between MBS and FAPs or between FAPs, a proposal [3GPP R4-093244] exists to extend the X2 interface, which is the interface defined in LTE for interconnection between eNBs. In such proposal [3GPP R4-093244], FAP's directly connected to the MME/S-GW may either have a direct X2 connection to nearby MBS or an X2 connection to the FAP GW.

[3GPP TS 36.423] specifies the X2AP protocol that defines the radio network layer signaling procedures of the control plane between eNBs in EUTRAN through the X2 interface. In X2AP protocol, the Load Indication Procedure is used to exchange interference coordination information among MBSs. It contains several information elements (see Table 15) such as:

- **Uplink Interference Overload Indication:** The Overload Indicator (OI) provides information on the uplink interference level (high, medium, low, …) experienced in each PRB. A maximum of 110 PRBs are possible.

- **Uplink High Interference Indication:** The High-interference Indicator (HI) provides information to neighboring cells about the PRBs upon which the cell intends to schedule its cell-edge users. It provides a two level report on interference sensitivity ('high interference sensitivity' or 'low interference sensitivity') per PRB (a maximum of 110). The target cell identifier for which the high interference indication is meant is also indicated in this IE.

- **Relative Narrowband Transmission Power (RNTP):** It provides information on the downlink transmission power per PRB.

IE/Group Name	Presence	Range	IE type	Semantics description
Message Type	M			
Cell Information	M			
>Cell Information Item		*1 to maxCellineNB*		
>>Cell ID	M		ECGI	Id of the source cell
>>UL Interference Overload Indication	O			
>>UL High Interference Information		*0 to maxCellineNB*		
>>>Target Cell ID	M		ECGI	Id of the cell for which the HII is meant
>>>UL High Interference Indication	M			
>>Relative Narrowband Tx Power (RNTP)	O			
>>ABS Information	O			
>>Invoke Indication	O			

Table 15. Table defined in document [3GPP TS 36.423V10.1.0 (2011-03), Table 9.1.2.1], where M stands for Mandatory and O for optional.

The receiving eNB may take such information into account when setting its scheduling policy, for instance, avoiding scheduling cell edge UEs for the PRBs with higher interference sensitivity. However, this is implementation specific.

Procedure for inter-FAP interference cost exchange

To compute the interference prices, each FAP must sent to any dominant interfering FAP a cost value per PRB that depends on three factors:

- The Lagrange multiplier associated to the power constraint (in the maximum rate approach) or the rate constraint of the user allocated at this PRB (in the minimum power approach). It is greater as the constraint is tighter, meaning that a small change in the constraint (maximum power or target rate) will affect greatly to the optimal value of the cost function.

- The sensitivity to the noise and interference in this PRB, reported by the FUE (eq. (44)).

- The cross channel information

In the SISO case, the cross channel information is the amplitude of the cross channel. As the sensitivity factor is also a scalar value, the parameter (interference cost) to be exchanged between FAPs is a scalar parameter. The cost transmitted from the *g-th* FAP to the interfering *f-th* FAP regarding the *c-th* PRB is:

$$\text{cost}_{g,f} = \mu_g \pi_g^c \left| h_{g,f}^c \right|^2 \quad (45)$$

In the MISO case the information to be exchanged among FAPs is no longer a scalar value but a matrix, as the cross channel is a *1xM* vector (the Lagrange multiplier and the sensitivity factor are scalar parameters). The information to be exchanged among FAPs is a rank one matrix. It can be fully characterized by the same scalar value as in the SISO case, along with a unitary cross channel.

$$\text{cost}_{g,f} = \mu_g \pi_g^c \mathbf{h}_{g,f}^{c\ H} \mathbf{h}_{g,f}^c = \mu_g \pi_g^c \left\| \mathbf{h}_{g,f}^c \right\|^2 \mathbf{u}_{g,f}^{c\ H} \mathbf{u}_{g,f}^c \quad (46)$$

In the MIMO case, it is also necessary to send a matrix (cross channel and sensitivity are matrices), but this matrix is not rank one. Each FAP must send, therefore, a scalar value and a unitary vector for each mode of the following matrix.

$$\text{cost}_{g,f} = \mu_g \mathbf{H}_{g,f}^{c\ H} \mathbf{\Pi}_g^c \mathbf{H}_{g,f}^c \quad (47)$$

With the information received from the surrounding FAPs, a potentially interfering FAP computes a global price per PRB. In the SISO case, if the global price is high, the FAP will avoid allocating large power in this PRB. In the MISO (and MIMO) case, the FAP will avoid the directions more sensitive to minimize the “damage" to the users connected to other FAPs. Therefore, the precoder will steers nulls in the direction of potentially interfered neighbors, despite the depth of such nulls depend on the potential ‘damage’ to these neighbors.

The protocol for pricing information exchange among FAPs is the following:

- Each FAP keeps a list of potentially interfering neighboring FAPs which are the FAPs connected to the FAP GW that have active users. The FAP will select an ordered subset (dominant interferers) among this set, according to the reports sent by the FUEs connected to. To avoid excessive overhead, control information will be sent only to the dominant interferers (a threshold needs to be defined).

- DL pricing information is sent to each dominant interfering FAP through the X2 interface.
- New DL pricing information from the same FAP overrides older DL pricing information.

For interference cost exchange new information elements need to be defined. Our proposal is to include a new information element in the way shown in Table 16. This information element contains quantized information regarding each one of the modes of the interference cost matrix to be exchanged between FAPs. A codebook containing a set of unit-norm quantization vectors is used to quantize a direction vector (for the MISO case, this direction vector will be actually the vector of channel measurements normalized by its amplitude, such that the quantization index captures information regarding only the ‘direction’ of the channel vector). Along with the quantization index corresponding to this unitary vector, a real number measuring the cost of the interference received in the reported directions is included as well.

As shown in Table 16, the DL interference cost indication (DLICI) message contains 3 items for PRB:

- The first item corresponds to the number of directions whose information is encoded. If the PRB is unused by the FAP sending the message, the interference cost is 0. In such a case, the number of reported directions will be 0. The number of reported directions will be 1 for SISO and MISO, and up to a maximum value that will depend on the number of transmit and receive antennas.
- For each encoded direction, a scalar cost value must be transmitted, requiring S bits per direction encoded.
- The third item corresponds to the quantization index for the direction vector from a predefined codebook. The number of bits to quantize each direction (T in the table) will be different depending on the number of transmit antennas (antenna ports) of the FAP for which the DLICI message is meant. For example, in the LTE standard 4 possible precoders are defined for 2 transmit antennas and 1 layer transmission, while for 4 transmit antennas and 1 layer transmission 16 possible precoders are defined. Notice that, if the FAP for which the DLICI message is meant has only 1 transmit antenna there is no need for direction feedback.

If the interference cost for the PRB is 0 (for instance if the sending FAP does not plan to allocate any user at the PRB or if the interference at the PRB has negligible impact) then only 1 bit is required for this PRB, exactly as in the Uplink High Interference Indication message defined in the current version of X2 for information exchange between eNBs.

IE/Group Name	Presence	Range	IE type	Semantics description
>>DL Interference Cost Information	O			
>>>Target Cell ID			ECGI	Id of the cell for which the DLICI is meant
>>>DL interference cost indication		*1 to Max Number of Resource Blocks (110)*		Each PRB is assigned a variable number of bits
>>>>Number of directions reported		*1 to Max Number of Directions*	R bits	First R bits correspond to the number of directions encoded for this PRB
>>>> Scalar cost value for each direction reported			Number of directions reported x S bits	S bits in the bitmap correspond to one reported direction.
>>>>Quantization index for the direction vector			Number of directions reported x T bits	T bits in the bitmap correspond to one reported direction.

Table 16. New information element for exchanging the interference cost information

4.6.1.3 Performance degradation due to the quantization of pricing

Quantization of pricing brings unavoidable degradation in performance. In this section we evaluate by simulation how important this degradation is.

We consider a scenario with 4 FAPs, each one with 2 users. Each user receives half of the total number of available PRB and the user target rate is 1.5 bps/Hz. Each FUE is interfered by the 3 FAPs different from the serving one. The average channel strength between each FUE and interfering FAP is 15 dB below the average channel strength between the FUE and his serving FAP.

Figure 62 left corresponds to the time evolution of the total transmission power for the 4 FAPs considered. The figure corresponds to a random channel realization in this scenario. The blue line corresponds to the results obtained in the SISO case without pricing (iterative waterfilling), while the red lines corresponds to the results obtained when interference cost information is exchanged among FAPs to compute the pricing values. Different numbers of bits to quantize the interference cost information have been considered.

Solid red line corresponds to perfect pricing knowledge (as if we use infinite bits to quantize the interference cost value sent from the serving FAP to an interfering FAP). Dashed lines correspond to the results when FAPs exchange a quantized version of the interference cost. With the purpose of having more resolution for smaller cost values, firstly we apply a logarithm transformation of the scalar cost value, followed by a uniform quantizer:

$$\hat{c}_{g,f} = Q\left(\log_{10}\left(\text{cost}_{g,f}\right)\right) \quad (48)$$

The receiving FAP will approximate the cost by doing the inverse operation

$$\text{cost}_{g,f} \approx 10^{Q^{-1}\left(\hat{c}_{g,f}\right)} \quad (49)$$

Two cases are considered: 2 bits per PRB or 3 bits per PRB. When quantizing the cost (if the cost is greater than 0), the lowest quantized level is 0.1 and the highest is 10. It can be observed that the degradation due to pricing quantization with only 2 bits is small. If 3 bits are used there is almost no degradation.

Let us consider now the individual FAPs power after convergence for different channel realizations. Figure 62 right represents the CDF of one FAP power after 60 iterations of the algorithm. 40 independent channel realizations have been considered to generate this figure. Some degradation because of the quantization can be observed for worst cases. Still there is a significant power saving when using quantized pricing compared to the non-pricing case.

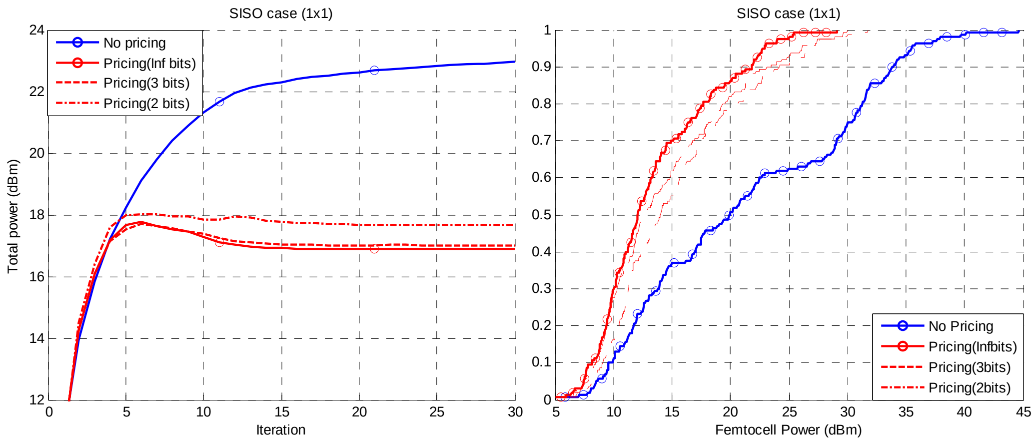


Figure 62. Left: Time evolution of the total transmission power for 4 FAPs (one random channel realization); Right: CDF of individual FAP power after convergence. SISO case, 4 FAPs, 2 users/FAP. Target rate 1.5 bps/Hz.

For the MISO case and a user target rate of 1.5 bps/Hz, the required power is significantly decreased when compared to the SISO case. Therefore, the interference from neighbor FAPs is also decreased and the advantage due to pricing seems to be marginal (see Figure 63). However, if the user requirements are increased, for instance to 2 bps/Hz (Figure 64), each FAP must increase its power to fulfill the target rate, with the consequent interference increase. In such a case, it is clear that the exchange of interference cost information helps to reduce the overall power. Notice, that the degradation due to the quantization is smaller than in the SISO case, considering the unitary cross-channel vector is perfectly known.

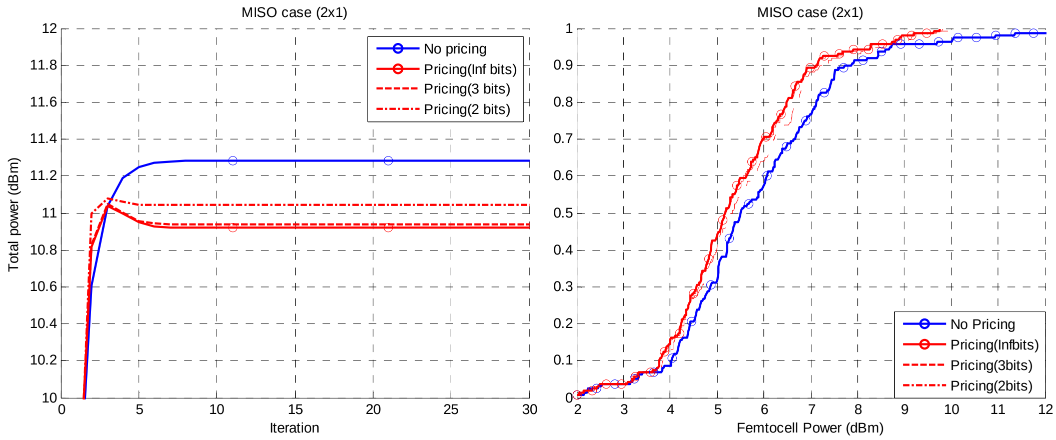


Figure 63. Left: Time evolution of the total transmission power for 4 FAPs; Right: CDF of individual FAP power after convergence. MISO case, 4 FAPs, 2 users/FAP. Target rate 1.5 bps/Hz. Unitary cross-channel vector is assumed to be perfectly known.

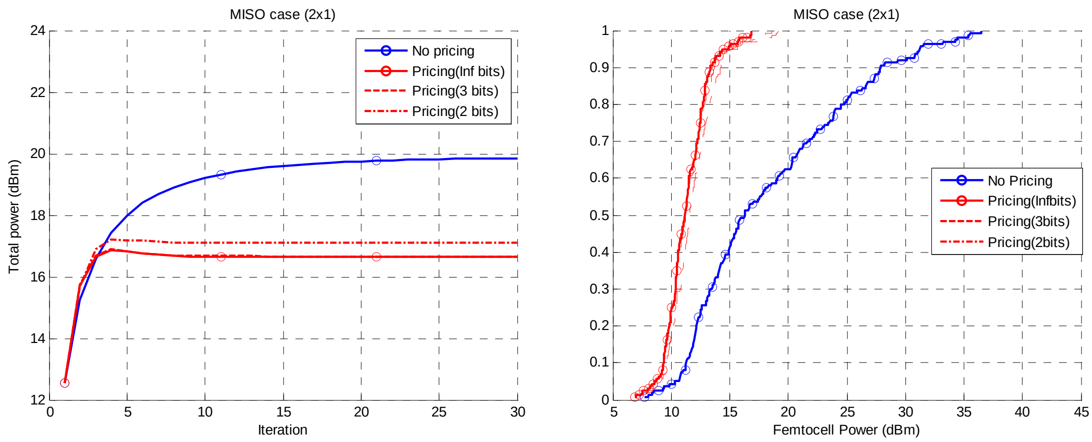


Figure 64. Left: Time evolution of the total transmission power for 4 FAPs; Right: CDF of individual FAP power after convergence. MISO case, 4 FAPs, 2 users/FAP. Target rate 2 bps/Hz. Unitary cross-channel vector is assumed to be perfectly known.

However, for the MISO case also the unitary channel vector needs to be quantized. Based on the beamformers defined in LTE standard, we have considered the following unitary vectors to quantize the unitary channel:

$$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix};\ \frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix};\ \frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix};\ \frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix} \qquad (50)$$

We have added also the following ones, corresponding to one single antenna selection:

$$\begin{bmatrix}1\\0\end{bmatrix};\ \begin{bmatrix}0\\1\end{bmatrix} \qquad (51)$$

While the performance of the pricing scheme degrades a bit more with respect to the case where perfect cross-channel knowledge is available (as in Figure 64), there is still a power saving compared to the case when pricing is not used. This power saving is 10 dB for the worst 20% of the cases, and it is even greater for the worst 10% or worst 5% cases.

This power saving, however, comes at the expense of an increased amount of overhead, which is high. For the MISO case, assuming 2 bits for the scalar cost value quantization, and 3 for the unitary vector quantization, a maximum number of 6 bits needs to be reported per PRB and dominant interferer. This means up to 660 bits that needs to be transmitted in the FAP-FAP interface at each iteration of the algorithm (an iteration could be done at time intervals equal to or greater than a sub-frame, i.e. 0.5 ms, and equal to or smaller than channel coherence time divided by the time required for the algorithm to converge). This is however a very worst case, since for those PRB with an interference cost equal to 0, only 1 bit is required.

Notice that we are quantizing the cross-channels directions based on the existing LTE codebook. These quantized directions will be used to steer the nulls of the precoders. The deep of these nulls should depend on the interference transmitted in the directions reported. Despite the quantized cross-channel directions will be (hopefully) close to the real ones, they are not exactly equal. For such a reason, and different from the case in Figure 64 where the unitary vector channel was assumed to be perfectly known, a perfect representation of the costs measured with the actual channel directions does not necessarily increase the performance of the proposed approach.

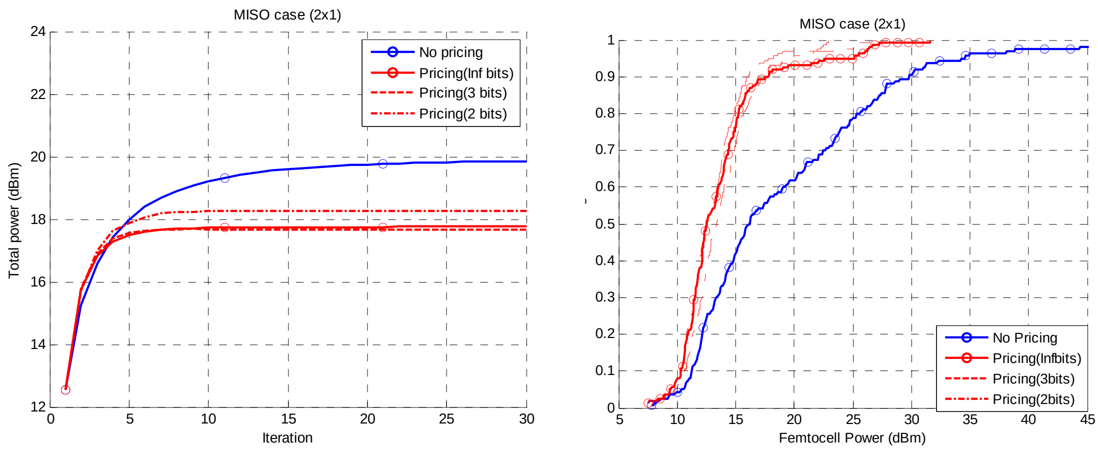


Figure 65. Left: Time evolution of the total transmission power for 4 FAPs; Right: CDF of individual FAP power after convergence. MISO case, 4 FAPs, 2 users/FAP. Target rate 2 bps/Hz. Quantization of the scalar cost value and the unitary cross-channel vector.

Finally, for the MIMO (2x2) case and a target rate of 3 bps/Hz, Figure 66 Left and Figure 67 Left show the time evolution of the total transmission power for the same channel realization for which previous results were obtained. Figure 66 Right and Figure 67 Right show the CDF of the individual FAP power for 40 channel realizations. Again the blue line corresponds to the results obtained without pricing, while the red lines corresponds to the results obtained when pricing information is exchange among FAPs with different number of bits allocated per control message. In Figure 66 only the scalar value for each one of the two modes of the interference cost matrix have been quantized. In Figure 67 both the scalar value and direction for each one of the two modes of the interference cost matrix have been quantized. Again, notice that when perfect feedback for the directions is not possible (Figure 67) there is no gain in coding perfectly (infinite bits for the scalar value) the cost values.

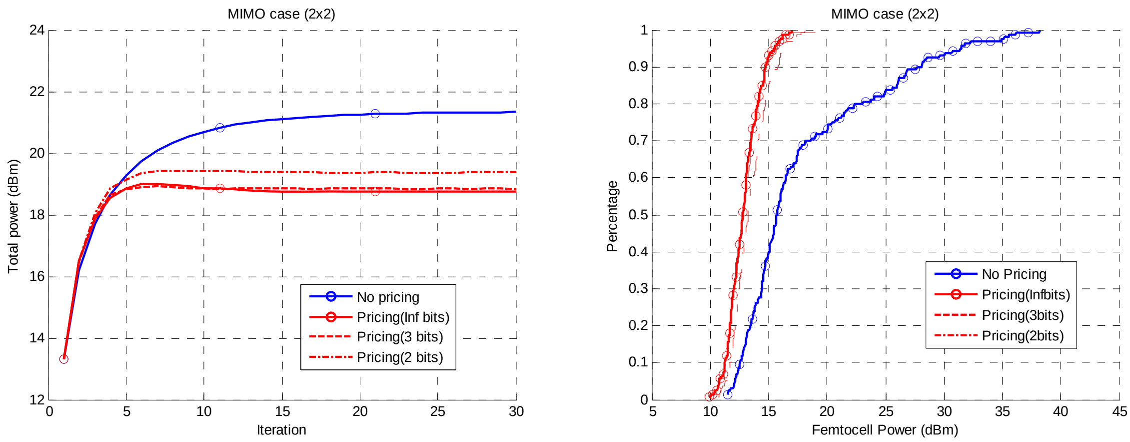


Figure 66. Left: Time evolution of the total transmission power for 4 FAPs; Right: CDF of individual FAP power after convergence. MIMO case, 4 FAPs, 2 users/FAP. Target rate 3 bps/Hz. Unitary cross-channel vector is assumed to be perfectly known.

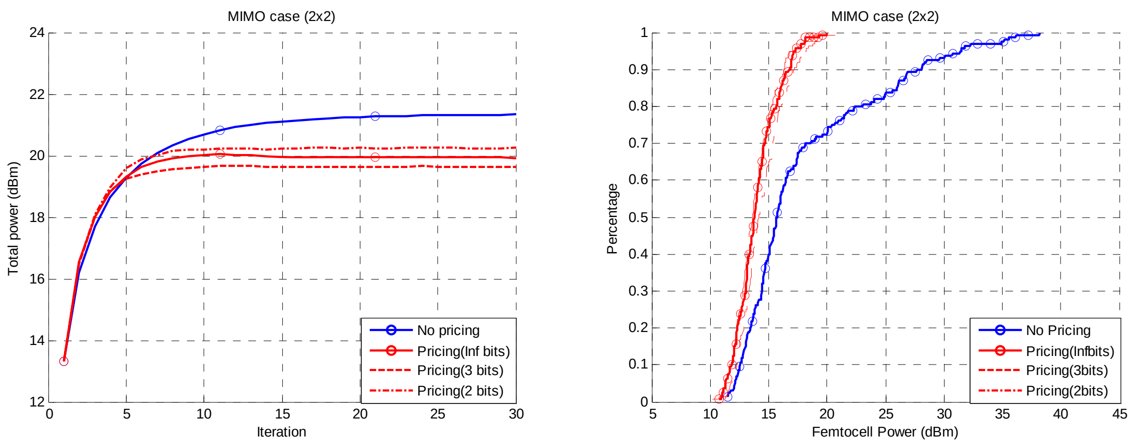


Figure 67. Left: Time evolution of the total transmission power for 4 FAPs; Right: CDF of individual FAP power after convergence. MIMO case, 4 FAPs, 2 users/FAP. Target rate 3 bps/Hz. Quantization of the scalar cost value and the unitary cross-channel vector.

4.6.2 LTE-A adapted pricing mechanism for MCS and bandwidth part selection

The design of precoders to minimize the total power or to maximize the weighted sum-rate requires feedback of the channel between a FUE and his serving FAP, even if coordination among FAPs is not considered. To that end, for each PRB, Channel Vector Quantization for reporting CSI information in LTE Uu interface is required, along with a real number that represents the SNIR measured at each channel eigenmode in this PRB. Doing so, the eNB has the flexibility to design the precoding matrix, which is not known by the UE in advance. This level of granularity, however, is not currently considered in LTE standard. As it will be explained below, the UE reports the maximum modulation and coding scheme (MCS) supported for a group of PRBs.

In WP3 a simpler and better LTE adapted pricing algorithm was proposed for interference coordination. More specifically, this algorithm considers on/off transmission at each resource block (no power control). Instead of the SNIR, UEs report the maximum MCS that can be used within the set of available resource blocks, along with a parameter (cost) that measures the MCS degradation because of neighbor FAPs transmissions. The results in WP3 demonstrated significantly higher performance as compared with no pricing, justifying the investments in unavoidable standard enhancements, which are however much simpler than for the previous algorithm as detailed below.

4.6.2.1 FUE procedures

FUE procedure for detecting and reporting Channel State Information (CSI)

Procedures for CSI reporting from UE to eNB are defined in the PHY layer description of LTE [3GPP TS 36.213]. Wideband type, multi-band type and MIMO type reporting are defined.

The CSI reports consist of the following indicators: channel quality indicator (CQI), precoding matrix indicator (PMI), and/or rank indication (RI):

- The CQI, used for link adaptation, is an indication of the data rate which can be supported by the channel, taking into account the SNIR and the characteristics of the UE's receiver. The CQI indicator is selected from 16 possible values for transmissions from 0.1523 to 5.5547 bits per symbol (QPSK and 16 QAM and different code rates). The first level is reserved for no transmission.

- The PMI is used for precoder-matrix/vector selection from a codebook subset. In the case of closed-loop spatial multiplexing, a UE feeds back to the eNB the preferred precoder from a predefined codebook, the precoder that would maximize the capacity based on the receiver capabilities.

- The RI informs about the number of useful transmission layers.

The proposed LTE-A adapted pricing mechanism for MCS and bandwidth part selection was described in WP3 for the SISO case. When more antennas are provided at both the transmitter and receiver side, the FUE feeds back the preferred precoder from the predefined codebook along with the supported MCS. Selecting the precoder also as a result of the pricing exchange will require each FUE reports and ordered list of preferred precoders per frequency band, along with the supported MCS for each one of them.

FUE procedure for reporting Channel State Information (CSI) of neighbouring femtocells and interference sensitivity

An intrinsic feature for the WP3 coordination algorithms, including the LTE-A adapted algorithm, is the use of interference prices. As described in 3D2, to compute the interference prices, a FUE needs to determine the cost of scheduling **each strong interfering** station DL transmission in one or more parts of the frequency channel. The cost for the user $u(g)$ due to the transmission of the *f*-th FAP in the *s*-th part of the frequency channel (sub-band) is:

$$\mathrm{cost}_{u(g),f}^{s} = \sum_{r=1}^{N} \pi_{u(g)}^{s,r} i_{u(g),f}^{s,r} \tag{52}$$

which is equal to the sum, over the *N* resource blocks in the *s*-th part of the frequency channel, of the product of two terms:

1. The sensitivity of the MCS reported for a given sub-band due to the **total interference** for each PRB in this sub-band, $i_{u(g)}^{s,r}$:

$$\pi_{u(g)}^{s,r} = -\left.\frac{\partial MCS_{u(g)}^{s}}{\partial i_{u(g)}^{s,r}}\right|_{\mathbf{i}_{u(g)}^{s}(0)} \tag{53}$$

2. The interference to be received from the *f*-th station when the *f*-th station schedules a DL transmission, $i_{u(g),f}^{s,r}$.

When the UE is equipped with one single antenna, the UE will perceive a scalar channel, $h_{u(g),f}^{s,r}$, and the interference to be received from the the *f*-th station when the *f*-th station schedules a DL transmission will be given by $P_f \left| h_{u(g),f}^{s,r} \right|^2$, with P_f the transmission power of the *f*-th station.

Based on the operational bandwidth part and beamformer selected by its serving station, each UE will report a cost. In case a neighbor interferer is equipped with several antennas, the UE will report a different cost for each one of the beamformers that the neighbor interferer can use in the given bandwidth part.

When the UE and the serving FAP are equipped with multiple antennas (MIMO), several transmission layers can be supported. The MCS employed at one transmission layer may be different than the MCS employed at the other transmission layers. Therefore the estimation of the "interference sensitivity" and the measurement of the interference caused by the activity of other FAPs have to be done for each transmission layer.

In order to support the proposed algorithm, the existing standards should support the calculation of the "interference sensitivity" (for each one of the transmission layers) and the measurement of the amount of interference to be caused by each strong interferer if the interfering station schedules a DL transmission in the selected frequency channel (for each one of the transmission layers), for each one of the possible beamformers the interfering station can use.

Furthermore, The Uu interface should support the transmission by the UE to his serving station of the interference cost associated to each strong interferer for each one of the transmission layers.

4.6.2.2 FAPs procedure

Each report of cost related to a specific UE, serving station and interference source station, will be shared between the FAPs and MBS in the area, using the X2 interface. To limit the traffic, the bandwidth part should be chosen such to reflect the frequency resources needed for UE scheduling: if a serving station decides not to schedule any users at a given bandwidth part, it does not need to distribute the cost for this bandwidth part. Otherwise, the serving station will distribute the cost to the dominant interferers. In case that the serving station is transmitting several layers, the reported cost will be the total cost for all the layers in the scheduled bandwidth parts. The generated traffic should be relatively low, due to the fact that only the "potential victim" UEs and stations will generate it.

Any neighbor station, *f*, scheduling a new user or reallocating a former one will select the operational bandwidth part and beamformer based on the MCSs reported by its own user and the costs reported by neighbor (potentially interfered) FAPs. Notice that both the MCSs reported by its own user and the costs reported by neighbor FAPs are given per beamformer (*w*) and sub-band (*s*). Therefore, a bidimensional selection in both frequency and space will be carried out:

$$\left(\hat{w},\hat{s}\right)=\max_{w\in\{W\},s\in\{S\},}\left(MCS_{u(f)}^{w,s}-price_{f}^{w,s}\right) \quad (54)$$

As explained in WP3, to avoid go back and forward on the same sub-bands, we use some memory to update the pricing values. For the *n*-th frame, the pricing values are computed as follows:

$$price_{f}^{w,s}\left(n\right)=\alpha\, price_{f}^{w,s}\left(n-1\right)+\left(1-\alpha\right)\sum_{\substack{g=1\\ g\neq f}}^{N_F} b_{g}^{s}\mathrm{cost}_{u(g),f}^{w,s}, \quad (55)$$

with b_g^s=0 if the *g*-th serving station does not use the *s*-th bandwidth part.

The high-level "costs" are shared, over the X2 interface, between the FAPs and MBS in the area. Therefore, it is necessary to define the information elements for distributing the "interference cost" over the X2 interface. As the bandwidth parts will be used as main resource elements, a common splitting of the channel width in bandwidth parts is required among the coordinated stations. A proposal of information element is given in Table 17. For each bandwidth part or sub-band, the first bit indicates if the cost is 0. If the cost is 0, no more bits are required to characterize the cost for this bandwidth part. If the cost is greater than 0, the next R bits are used to report a quantized version of the reported cost for each one of the possible *S* beamformers the neighbor station can use.

IE/Group Name	Presence	Range	IE type	Semantics description
>>DL Interference Cost Information	O			
>>>Target Cell ID			ECGI	Id of the cell for which the DLICI is meant
>>>DL interference cost indication		*1 to Max Number of bandwidth parts*		Each *bandwidth part* is assigned a variable number of bits: 1+RxS
>>>>Cost is greater than 0			1 bit	If 0, cost is not transmitted for this bandwidth part
>>>> Cost			RxS bits	R bits in the bitmap correspond to the reported bandwidth part and each one of the possible S beamformers

Table 17. New information element for exchanging the interference cost information

4.6.2.3 Interaction between *MBS and FAPs*

The algorithms investigated in activity 3A2 (D3.2) are scalable with the number of users and applicable to any type of transmitting terminal. While previous procedures and messages involving FAPs can be extended directly to MBSs, we can identify, however, three different operational modes of the coordinated algorithms as a function of the role of terminals involved in the downlink (DL) coordination:

1. **MBS and FAPs operate in the same band with same role.** FAPs and MBSs design their resource allocation considering the pricing values (or interference prices) generated by their neighboring and interfered terminals (MUEs and FUEs).

2. **MBS and FAPs operate in orthogonal bands.** Only FAPs design their resource allocation using the pricing values generated by their neighboring interfered FUEs. In this case, the MUEs are scheduled in a different band and they do not generate any pricing value

3. **MBS and FAPs operate in the same band with different role.** FAPs design their resource allocation taking into account the pricing values generated by the interfered MUEs and FUEs. However, MBS do not consider the pricing values generated by the interfered FUEs. In this way, we capture the fact that MUEs have a higher priority than FUEs.

4.6.2.4 Performance degradation due to the quantization of cost information

In this section, we compare the ideal results obtained in 3D2 with the performance obtained when quantization is done. Furthermore, we include results for the MISO case, using the codebooks already defined in LTE-standard. We consider the third of the possible modes of interaction between MBS and FAPs defined above. As in 3D2, we consider one FAP area (FAP dual-strip zone) within the coverage area of the MBS, and the following parameters:

- Channel bandwidth: 20MHz with four bandwidth parts corresponding each to 25 RBs, same as in 5MHz;
- Number of UEs per FAP: 1, SISO mode and MISO mode (1 antenna for the UEs, 2 antennas for the FAPs, and 4 antennas for the MBS)
- Number of UEs served by MBS and placed in the FAP area: 2 (the MBS will allocate these 2 UEs in two separate bandwidth parts, each one of 5 MHz);
- The dual-strip deployment was considered over a number of floors varying between 1 and 6;
- One serving station considers itself interfered if the average SNR received from an interfering FAP is greater than the SNR of the serving station minus 15 dB.

A logarithm transformation of the cost value is employed, followed by a uniform quantizer. The highest level for the cost reported corresponds to 5.55 which is approximately the highest MCS supported. The lower level for the cost reported is the 1% of this value.

3 bits at most are considered for each frequency part. The first bit indicates if the cost is 0. If the cost is different from 0, 2 bits are used to encode the cost value for each one of the possible beamformers of the neighbor station. For 2 antenna ports and 1 layer transmission, there are 4 possible beamformers in LTE. We consider these 4 beamformers plus the 2 beamformers corresponding to transmission from one single antenna (1 antenna port, 1 layer transmission). For the MBS, we have considered 20 possible beamformers: the 16 beamformers defined in the standard for 4 antenna ports and one layer transmission plus 4 beamformers corresponding to the selection of one single antenna. Notice, however, that no cost is reported to the MBS as we are considering the third mode of interaction between MBS and FAPs defined above.

In the following figures the blue line corresponds to the case with no pricing exchange, the solid red line corresponds to perfect pricing exchange, and the dashed black line corresponds to quantized pricing exchange.

For low FAPs densities, it is expected to receive a low number of cost values (possibly only in a subset of sub-bands). It may happen that a FAP decides to use a sub-band with a worse MCS if the difference between the MCS and the received cost is more favorable. The computed costs are pessimistic approximations for the degradation of the supported MCS in a neighbor FAP, but the decision regarding the use of a given bandwidth part and beamformer is binary. Therefore, it may happen that the error due to quantization compensates the pessimism of the approximation. This effect however is random, meaning that it can either help or not to the total rate. As the FAPs density grows, however, costs will be received for all the sub-bands and possibly from several neighbors. Therefore, despite the costs transmitted are still approximations, detailed information helps to sort the sub-bands appropriately to make a better decision regarding which sub-band should be chosen to deteriorate less the performance of the neighbors and therefore the total sum-rate. Both effects are observed in the next figures. Figure 68 shows the average FAP throughput (left) and the MBS throughput (right) vs. the average number of active FAPs in the area. There is a slight variation due to quantization for the average FAP throughput, while for the MBS throughput a small degradation is noticeable when the density of FAPs increases.

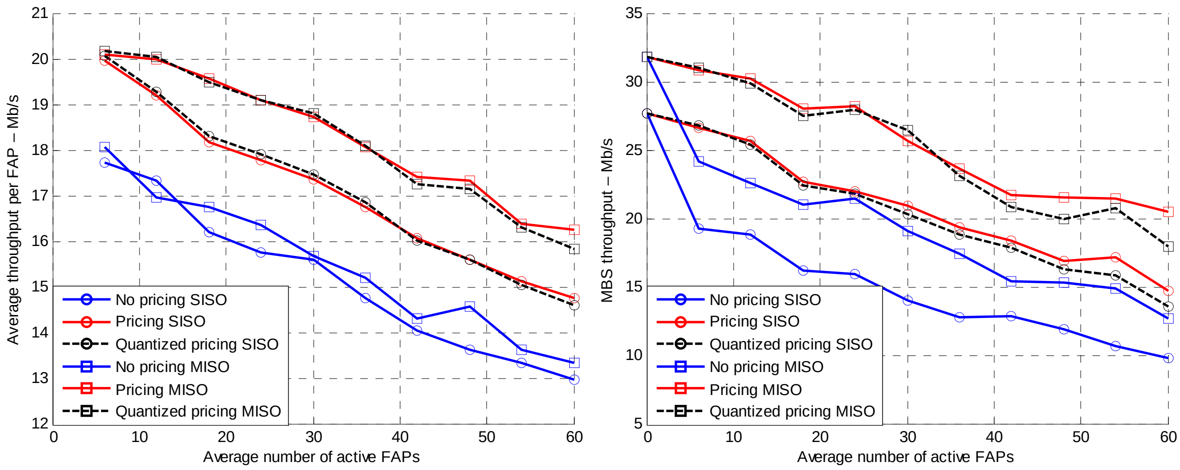


Figure 68. Left: Average FAP throughput vs. average # of FAPs; Right: MBS throughput vs. average # of FAPs.

Figure 69 depicts the percentage of FUEs (left) and the percentage of MUEs (right) supporting the maximum MCS versus the average number of active FAPs in the area. Again, there is a slight variation for the best users, as the percentage of users that are able to use the maximum MCS is practically the same considering costs quantization.

In Figure 70 Left, is shown the minimum MCS for the best 80% of FUEs vs. the average number of active FAPs, while in Figure 70 Right it is shown the same for the MUEs. Again, while the effect of quantization is not noticeable for the FUEs (despite at some point the next MCS is selected), but it is noticeable for the MUEs as the density of FAPs increases.

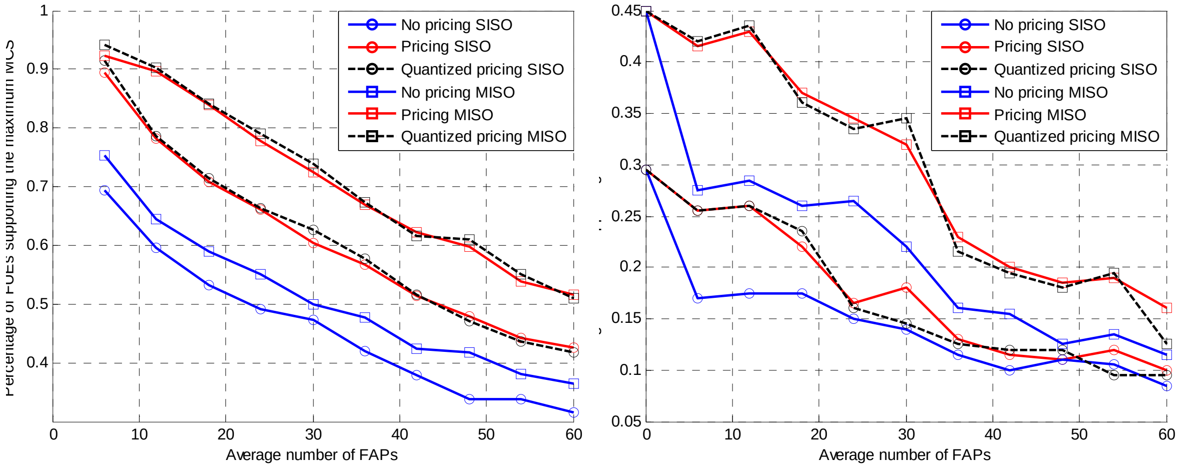


Figure 69 Left: FUEs supporting the maximum MCS; Right: MUEs supporting the maximum MCS

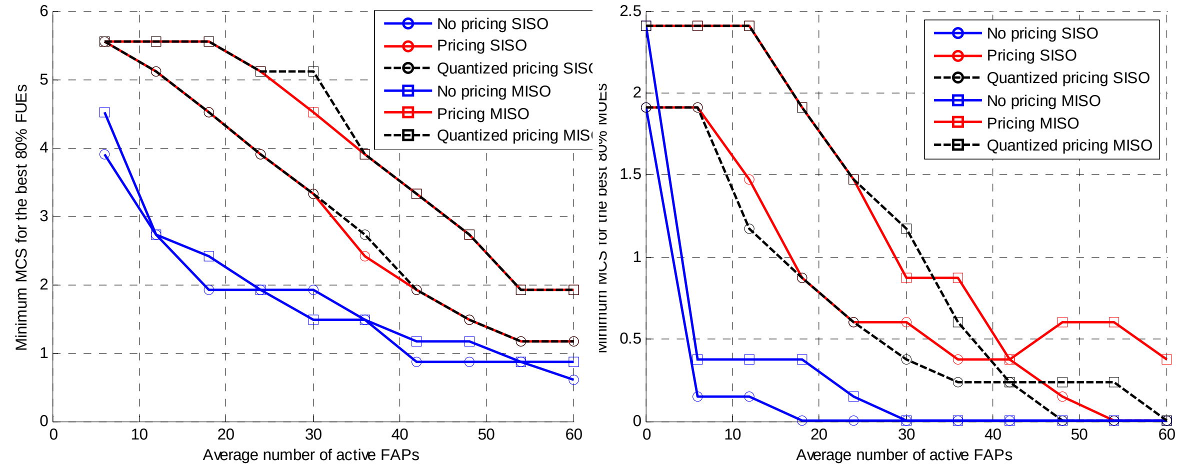


Figure 70: Left: minimum MCS for 80% FUEs; Right: minimum MCS for 80% MUEs

4.6.2.5 Overhead due to pricing

In previous simulations, the total interference is simulated, but the information costs are sent only to the main interferers. An interferer is a significant one if the average signal strength received from this station is between 0 and 15 dB below the signal strength of the serving station. This threshold has been shown to be good enough to obtain a performance improvement in the pricing approach. A study of the number of significant interferers was done in 3D2 for the FREEDOM scenario, considering this threshold. The average number of dominant interferers detected by the FUEs was observed to be lower than 2 in the FREEDOM scenario, even for the highest FAPs deployment density. The number was greater for the MUEs deployed within the FAP area, with a number of dominant interferers ranging between 3 (for the lowest density of FAPs) and 20 (for the highest density of FAPs).

In WP4, we have evaluated the loss due to quantization. It has been shown that quantizing each cost value with just 3 bits (at the most) per allocated sub-band and beamformer provides a very good performance. Considering two dominant interferers and 3 bits for the quantization means 6 bits per FUE that can be sent no faster than 5 ms (sub-frame duration). This means an average overhead in the Uu interface equal to 12 kbps (for very high densities) for the pricing exchange between FUEs and

FAPs in the SISO case. This means an average overhead in the X2 interface equal to 48 kbps (considering 4 bandwidth parts) for the pricing exchange between FAPs in the SISO case. In the MISO case, these numbers have to be multiplied by the number of beamformers that each neighbor can use. For the MUEs deployed within the FAP area, the average overhead ranges from 18 kbps (for low densities, average number of dominant interferers equals to 3) and 120 kbps (for very high densities, average number of dominant interferes equals to 20). The traffic generated by the MBS in the X2 interface would be therefore 72 and 480 kbps respectively (SISO case). The overhead in the X2 interface could be smaller than previous values if the FAP/MBS does not need to schedule users in all bandwidth parts.

5 SCHEDULING

This section is logically divided into two parts. The first part proposes new control procedures to mitigate interference and to improve performance of opportunistic scheduling. The second part focuses on efficient scheduling taking the quality of femtocell's backbone into account.

5.1 Timer based interference mitigation (femto to macro downlink interference mitigation)

5.1.1 Principle and control procedures

One possible mitigation technique consists in forbidding a given set of resource blocks to be used in the FAPs. When outdoor UEs under macro cell coverage suffer from nearby femtocell interference on the downlink, then they can fall back to using only resource blocks that are forbidden in femtocells.
However this technique introduces constraints both in the UE under femtocell coverage and those under macro cell coverage. Such constraints will degrade performances of opportunistic scheduling algorithms. The worse degradation is expected for the outdoor user under macro cell coverage and under femtocell interference: they are constrained to use only a possibly small subset of resources.

The current procedure proposes to have similar constraints in a dynamical way in order to reduce the expected loss in terms of opportunistic scheduling performances. The principle consists in allowing the MBS to send commands to FAPs, in order to forbid the use of a specific set of resource blocks for a given period of time. It is based on timers in this sense that once the timer expires in the FAPs, the corresponding set of resource blocks becomes available again. It should be noted that such technique assumes time synchronization between macrocell and femtocells. At least, femtocells have to be synchronized to their umbrella macro cell.

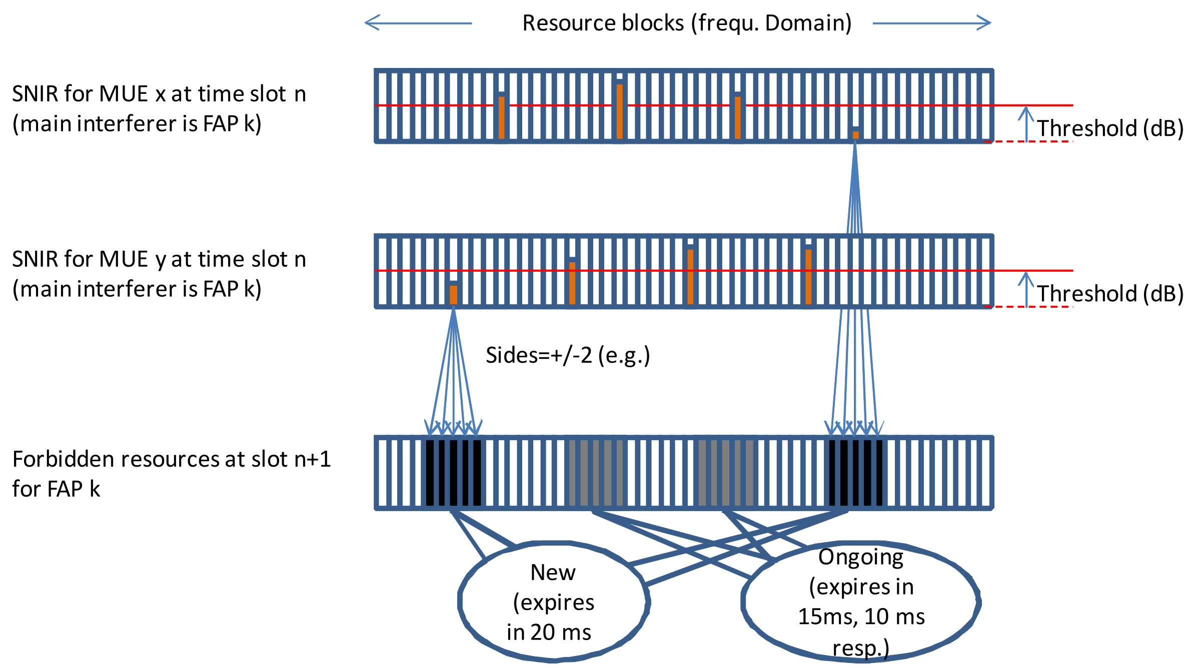


Figure 71: principle of timer based interference mitigation

The Figure 71 details how the algorithm works in a graphical way. It assumes 2 different Macro attached UEs experiencing different SNIR on different assigned resource blocks, and having a given FAP as the main interferer. For each UE it is assumed that one resource block is attached to an SNIR that falls below a given threshold. Then the macro station takes the initiative to send to the offending

FAP a command requiring that the respective resources should be forbidden in this FAP for a given timer period (e.g. 20 ms). It also automatically includes the neighbor resources, e.g. 2 side resources on the left and 2 on the right. The figure also assumes that other resources have been forbidden in the past and have their timer running (e.g. there is 15 ms remaining for one set and 10 ms remaining for the other).

The following procedure is foreseen:

From MeNB to HeNB:

Forbid the following resources for a given period of time, includes:

A set of contiguous resource block forbidden to the target HeNB

An expiration timer values expressed as a number of TTI.

5.1.2 Performance evaluation

Timer based interference mitigation has been evaluated according to the basic assumptions presented in section 3.4.1. A dedicated deployment layout has been defined for this simulation. The simulated area is a 1 kilometer wide square, with a MBS located on its middle. Fifty single floor houses are dropped in the area. Each house contains one FAP and 2 terminals, one being attached to the said FAP, and the other one being attached to the MBS, given the assumption that this second terminal is not allowed to attach to the local FAP. Both terminals and FAPs are located in random places in each house.

Then, beyond the said 50 FAP-attached indoor terminals and the said 50 MBS-attached indoor terminals, we also have 100 MBS-attached outdoor terminals, located at random outdoor positions. Hence the simulated system contains:

- 1 MBS
- 50 indoor FAPs,
- 50 FAP-attached indoor terminals,
- 50 MBS-attached indoor terminals.

The other assumptions are similar to those of [FRED4.1], section 5.2:

- 20 MHz LTE channel,
- MBS Tx power at 46 dBm (no power control)

FAP Tx power at 15 dBm (no power control),The bit-rate sent to all macro-attached users is presented on the x-axis in all of the following charts. For each such bit-rate, the average loss ratio is presented on the y-axis. It is averaged either on all macro-attached terminals, or on all femto-attached terminals.

All plots in Figure 72 shows at least 2 curves: one that simply assumes no interference at all (called “NoIntf”), which could be reached if, e.g., macro and femto cells would use different RF bands, and another one (called “Intf”) with interference assumed and without any mitigation technique. If we read such curves we see that for a maximum loss ration equal to 0.1 (e.g.) the femto to macro interference decrease the average bit-rate that can be sent to macro-attached users from 330 kbit/s down to 180 kbit/s. Note that x-axis always concerns the bitrate injected to MUEs. The bitrate injected to FUEs is a constant one equal to 10 Mbit/s. Therefore the plots on the right show the loss ratio of MUEs as a function of bitrate injected to MUEs, which can only be increasing, while the plots on the right show the loss ratio of FUEs as a function of the bitrate injected to MUEs, which is typically decreasing.

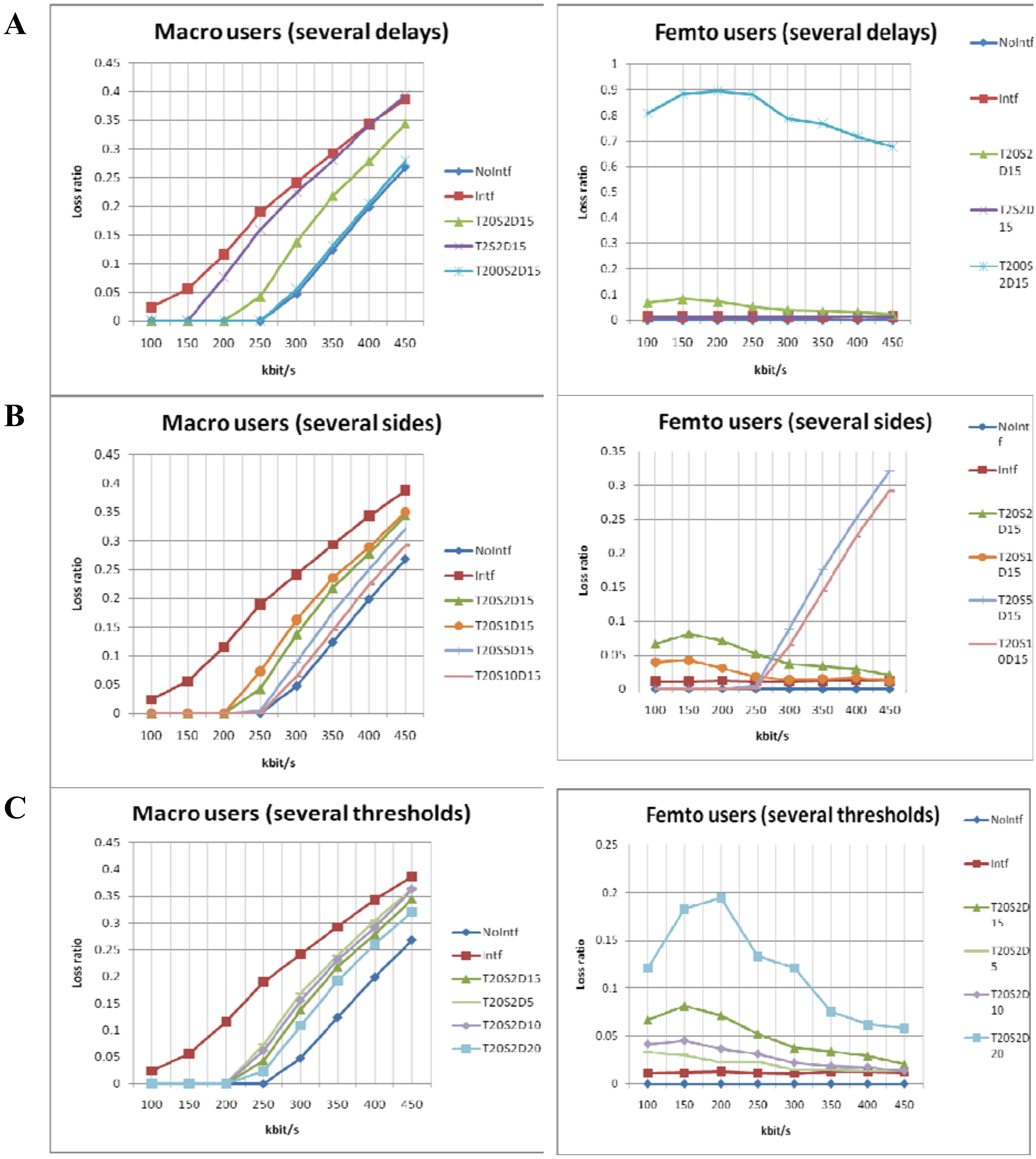


Figure 72: Evaluation of timer based interference mitigation according 3 different configuration parameters.

Then several curves are presented with timer based interference mitigation. Each figure part presents the effect of a particular parameter:

- Figure 72/A presents the effect of timer delay,
- Figure 72/B presents the effect of side dimensioning (explained below)
- Figure 72/C presents the effect of interference threshold (explained below).

All curves that assume timer based interference mitigation present intermediate results that are better than “Intf” but not as good as “NoIntf”. The algorithm should be tuned with the parameters that give the closest possible curve with respect to “NoIntf”.

The typical delay for forbidding resources is set to 20 ms. It means that a given resource is forbidden only for a period of 20 ms. However, 2ms and 200 ms are also considered in the first 2 plots.

When a macro user experiences degradation on a given frequency resource because of a femto user, the MBS decides to forbid the corresponding FAP to use this frequency resource for some period, together with a given number of frequency resources on each sides. In the simulation the typical behavior is to forbid 2 frequency resources on each side as well. However, results presented in the 2 middle plots also assume 1, 5 and 10 for the number of frequency resources on each side.

When a macro user experiences some degradation on a given frequency resource because of a femto user, the MBS only decides to forbid resources if the resulting signal to interference ratio is below a given threshold. The typical value is 15 dB. However, the last 2 plots also present results with 5dB, 10 dB, or 20 dB.

From the 2 first plots in Figure 72 it can be seen that the higher the timer delay is, the best it is for macro-attached users. However, when the delay is too long, most FAP frequency resources become forbidden and the femto users experience a bad Quality of Service. As an example, if the timer is set to 200 ms the loss ratio experienced by femto users is beyond 0.7, which is not acceptable. A good compromise for timer delay is 20 ms. Such a value maintain the average loss rate of femto users below 0.1.

From the next 2 plots in Figure 72, we see that the larger is the side dimensioning, the better it is for macro-attached users. However is also affect femto-attached users in a negative way so that a side made of 2 frequency resources appears as a good compromise. It maintains the average loss ratio of femto-attached users below 0.1.

From the last 2 plots in Figure 72, we observe that the higher is the threshold, the best it is for macro-attached users. However it also translated into worst QoS for femto-attached users. A good compromise if to set the threshold to 15 dB as it maintains the average loss ratio of femto-attached users below 0.1.

5.1.3 Conclusion

Timer based interference mitigation appears as an efficient algorithm for reducing femto to macro interference effects on the downlink. This technique is compatible with the use of opportunistic scheduling, and can be considered in case of closed subscription access models as well.

5.2 Backhaul aware Scheduling

Backhaul plays an important role in femtocell deployment. Backhaul tailored for macrocell base stations (MBSs) have performance guaranties and engineered continuously as the link occupancy increase. Therefore there is no performance issue affecting the radio performance; hence most scheduling in MBS including WiMAX/HSPA/LTE, is designed to work with ideal backhaul.
It is different with the backhaul for FAPs. In order to achieve mass deployment of FAPs, mobile operator should make use of existing backhauls (xDSL, Fixed Broadband Wireless, FTTx, etc.) belonging to customers. Most broadband accesses for residential customers are mainly designed for internet access. Depending on the target customer, an ISP may offer different class of service based on QoS profile such as best effort, non-real-time polling service, real-time polling service, and unsolicited grand service. In this case, FAP should deal with backhaul limitation including:

a. Various link speeds (1 Mbps, 2 Mbps, 4 Mbps, etc.)

b. Various Service Level Agreements between end user and ISP

c. Traffic variation in each network segment including from access link to Access Node (DSLAM/MSAN), Access Node to Backbone (such as DSLAM-Metro Ethernet), and from backbone to the FAP Gateway in Mobile Operators core networks.

5.2.1 Bottleneck in xDSL

The study was started from exploring the effect of bottleneck in the backhaul link. The bottleneck happens when the following conditions occur:

a. The backhaul link speed is below maximum data rate supported by FAP (radio part).

b. Congestion in the backhaul link is happened due to background traffic.

The performance of a video traffic in xDSL link is explored with various link speeds. Since the study focuses on the backhaul side, BM3 scenario was used but without a macrocell (as interferer) to limit the interference issue affected the backhaul study.

The delay of video user using mixed traffic scenario is displayed in the next figure. It can be seen from the graph that when the xDSL link speed is 6 Mbps, the delay is about 69 ms. The delay sharply increases to 235 ms when the link speed is 4 Mbps.

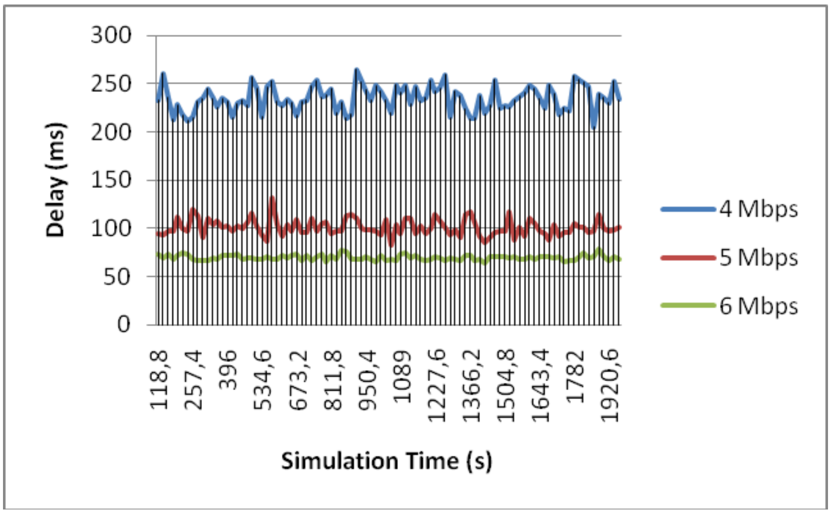


Figure 73. Delay performance of DL video traffic over various xDSL link speeds

Next figure shows the delay of video user using scheduling on different nodes. The xDSL link speed is set to 4 Mbps.

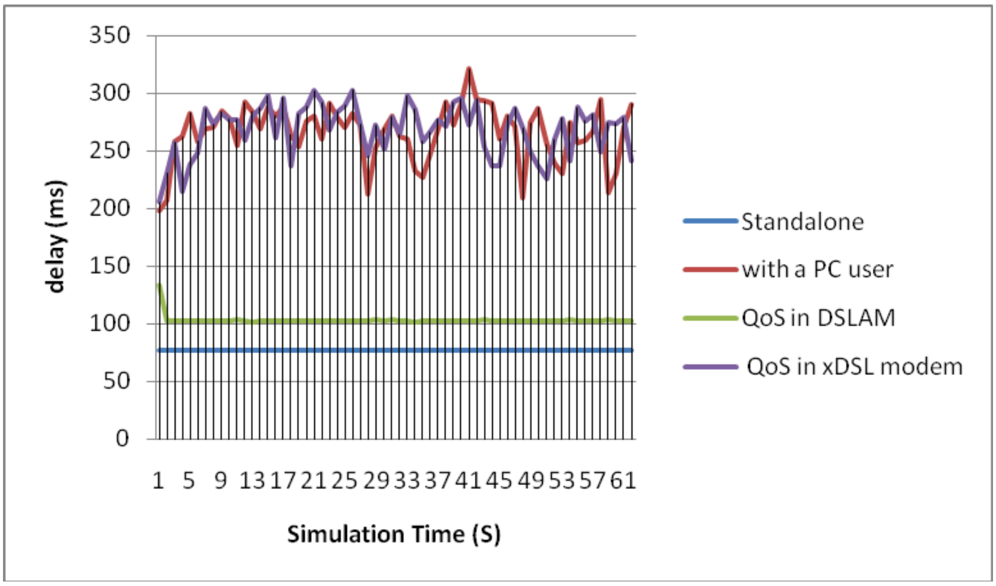


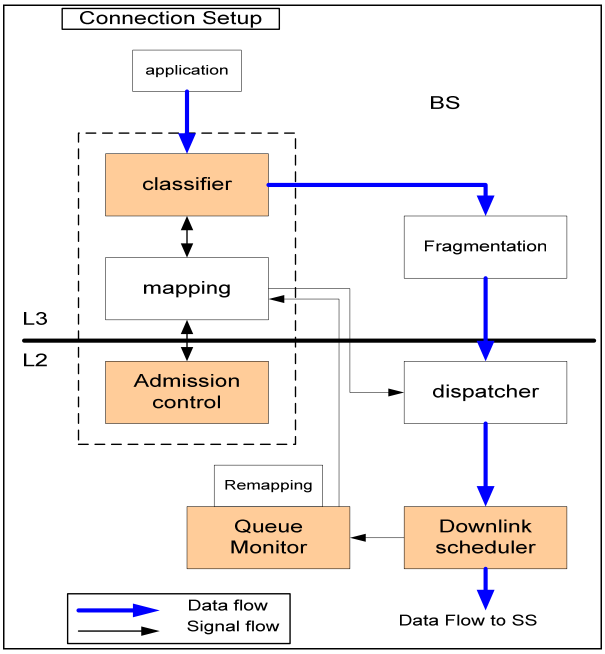
Figure 74. Delay performance of DL video traffic

When there is only a single Femto UE downloading a video streaming, the delay is about 77 ms. As soon as a PC user connects to xDSL modem and uses HTTP services, the delay of video user increases to 266 ms. We observe the possibility to see whether QoS in xDSL modem can improve the delay. It can be seen from Figure 74 that the implementation of QoS in xDSL modem does not improve the delay since the xDSL modem cannot recognize the priority traffic coming from Femtocell users. In this case there is no QoS mapping between scheduling implemented in xDSL modem and the one in Femtocell. In reality this situation happened when femto traffic and PC traffic uses same PVC. When the priority traffic is implemented in DSLAM the delay is improved, since DSLAM can recognize the video traffic and give higher priority over HTTP traffic.

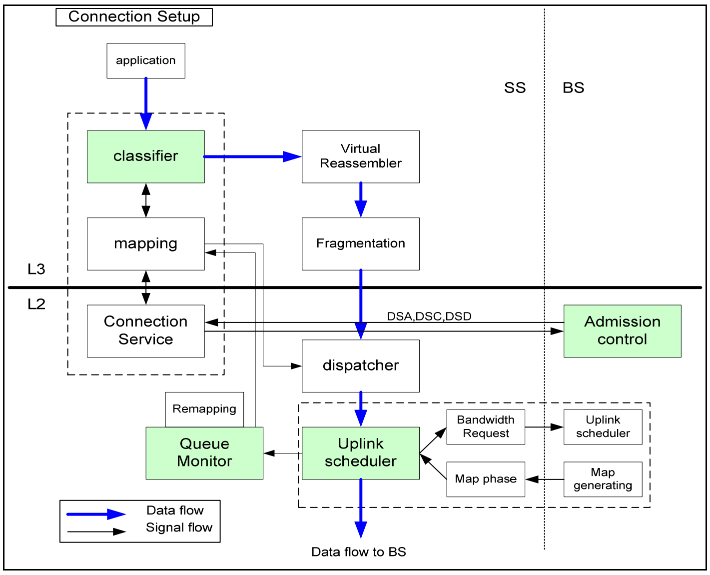
5.2.2 Admission Control Procedure

In order to develop backhaul aware scheduling we also conduct study on classifier, admission control, and queue monitor, which should be working collaboratively with scheduling algorithm being proposed. Figure 75 illustrates QoS Framework in WiMAX.

In connection setup, there are three functional blocks between layer 2 and layer 3, namely classifier, mapping and admission control. Information from the classifier and QoS mapping in Layer 3 is required by FAP to manage bandwidth allocation in admission control in layer 2. The classification of the incoming data packets is necessary for identifying the service associated with the connection identifier (CID). The classifier will analyze the packet whether it contains information related to priority marking (i.e., IEEE 802.1q and IEEE 802.1p as been studied in [Carmo05]) or any QoS parameters from upper layer (i.e., QoS parameters from Ipv6). The main task of the classifier is to match the CID of the incoming packets with the service class they belong to and to queue such packets in their relevant buffers. As the result, it will save up the time required for the bandwidth request process. Another important task of the classifier is to mark the time of each incoming packet according to its arrival time. This information is exploited by the buffer manager which recognize when a queued packet’s timeout expires, i.e., when its waiting time exceeds the maximum tolerated latency.



(a)



(b)

Figure 75. QoS Frame works in the downlink (a) – uplink (b) mode [Yiting07]

Connection Admission Control (CAC) maintains the QoS of new and existing connections by preventing overload. QoS based CAC can be used for a new connection request, which is classified into a particular queue depending on the service class. QoS-CAC treats the UGS connection queue with the highest priority, followed by rtPS and then by nrtPS queues as shown in Figure 76.

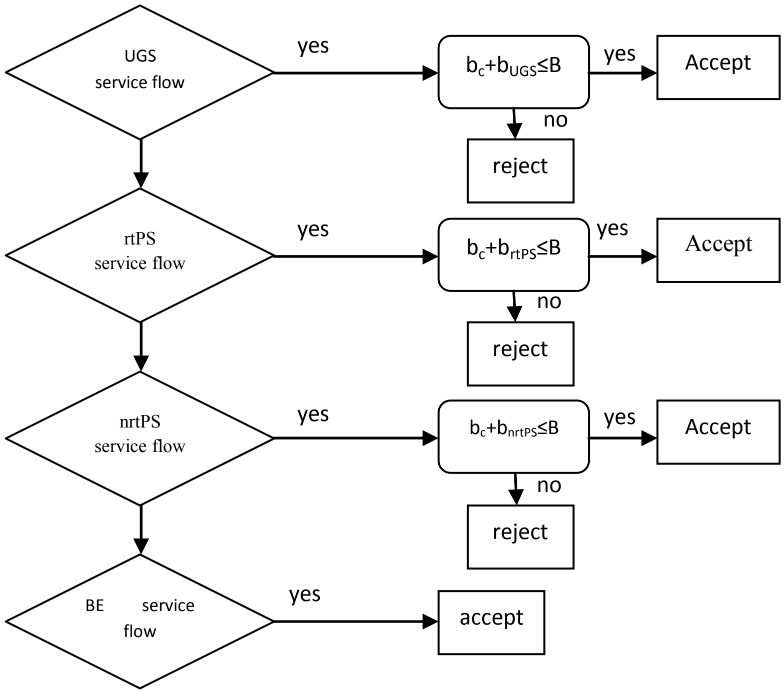


Figure 76. Admission control rule [Yiting07]

[Yiting07] implements a simple-rate-based admission control scheme in which a new service flow must inform the required bandwidth and the BS will check if there is enough capacity for the new flow. A new rtPS flow with bandwidth requirement B_{rtPS} is accepted when the remaining capacity, i.e., the total bandwidth B (radio capacity) is greater than $B_{allocated}$ (current allocated bandwidth) and B_{rtPS}. Moreover, since the characteristics of the flow in each service type varies, the required bandwidth defined for each service type should be different. So the admission control should recognize the bandwidth requirement of each QoS.

We study the possibility to modify the admission control mechanism by considering the nature of FAP both in radio part and backhaul part. The admission control proposed in [Yiting07] only considered the total bandwidth B (in radio part). This is valid when backhaul quality link is ideal (overbooking and no congestion are maintained). However, for femtocell case the algorithms should also consider the total link speed (B_{link}) and current bandwidth used in backhaul link (B_{curr_load}). So the bandwidth for new service flow should be granted when the bandwidth request (new service flow) and current allocated bandwidth (existing service flow) is lower than $\min(B, B_{link})$.

In IEEE 802.16 before a subscriber station can initiate a new connection, it must first make a request to the FAP with the service contracts required. The FAP may reject the request based on its ability to uphold the requirements. We expressed the need for the admission control in order to control the usage and allocation of bandwidth resources for various traffic classes requiring certain QoS guarantee or not according to the current traffic load of the system. It is possible that the FAP admits a connection based on statistical QoS, where, on average, all connections would not have their QoS satisfied, or that the FAP could have a stricter model where QoS is absolutely guaranteed, even in the worst case scenario. Therefore, effective decision making mechanisms for allocating bandwidth to different QoS are needed.

We describe how to provide a compromise between differentiate services by subdividing the available bandwidth into sections. Depending on the fair service (based on our objective), the allocation bandwidth would be dedicated to some or all classes. This allows more live up to the QoS requirements of the different user types while maintaining higher network utilization.

As in IEEE 802.16 UGS and rtPS connections have higher priority due to carrying data of real time applications, it would be desirable, from both user and network provider point of view, to prioritize the connection requests of this classes over an nrtPS connections request in admission control policy or in other words we do some treatment for nrtPS connection to get bandwidth for UGS and rtPS connections. Parameters used in this chapter are as follow:

- B: the total bandwidth
- $R_{UGS:}$ reserved bandwidth for UGS
- R_{rtps}: reserved bandwidth for rtPS
- r_{UGS}: Traffic rate of UGS
- r_{rtPS} : traffic rate of rtPS
- $B_{allocated}$: current allocated bandwidth
- $r_{nrtps}^{\max}$: maximum sustained traffic rate nrtPS connections
- $r_{nrtPS}^{\min}$: minimum reserved traffic rate nrtPS connections
- n_{nrtPS}: amount of nrtPS connections

If admission controls receives or rejects a UGS connection is based on the following condition:

$$B_{allocated} + r_{UGS} \leq B - R_{rtPS} \quad (56)$$

UGS to be accepted, admission control will cutting admitted nrtPS connection bandwidth in order to collect enough bandwidth for servicing the new request and will be rejected if there was no room for cutting nrtPS connections.

$$\begin{aligned}
&B_{allocated} = (r_{nrtPS}^{\max} - r_{nrtPS}^{\min} - \sum cut_{nrtps}) * \eta_{nrtPS} \\
&\text{If } r_{request}^{nrtPS} \leq B_{allocated} \text{ then} \\
&\qquad \text{Proportion } cut_{nrtPS} = \frac{r_{request}^{nrtPS}}{\eta_{nrtPS}} \text{ and then reduce nrtPS connection} \\
&\qquad \text{Update } \sum cut_{nrtPS} = \text{Proportion } cut_{nrtPS} \\
&\text{end}
\end{aligned} \quad (57)$$

Whenever the admission control receives new nrtPS connection request, the connection admits the system at the rate ($r_{nrtPS}^{\max} - \sum cut_{nrtPS}$) if:

$$B_{allocated} + r_{nrtPS}^{\max} - \sum cut_{nrtps} \leq B - R_{UGS} - R_{rtPS} \quad (58)$$

Whenever an admission control receives an rtPS connection request the decision to accept or reject it is made by checking whether

$$B_{allocated} + r_{rtPS} \leq B - R_{UGS} \quad (59)$$

Same as treatment for UGS, rtPS to be accepted, admission control will be cutting admitted nrtPS connection bandwidth in order to collect enough bandwidth for servicing the new request and will be rejected if there was no room for cutting nrtPS connections. The admission control always accept the BE connection request but no bandwidth is reserved for this class of connections, as it is not necessary to provide any guaranteed service for this class.

5.2.3 Backhaul-aware Model

As described in the Section 3, the FAP parameters used in the model can be seen in the next table. The network model also can be seen in the following figure.

Parameter	Value
PHY profiles name	Femtocell
Frame Durations (ms)	5
Symbol Duration (μs)	102,86
Number of Subcarriers	512
Duplexing Technique	TDD with Sym Ratio 25:21
TC Sublayer Overhead factor	0
Frequency Band	2.3 GHz (5 MHz)
Frequency Division (UL zone)	512-FFT PUSC
Frequency Division (DL zone)	512-FFT PUSC
frame Preambles(symbols)	1
TTG (μs)	106
RTG (μs)	60
BS Antenna Gain (SISO)	5 dBi
BS Transmit Power	0.1W
UE Antenna Gain	0 dBi
UE Transmit Power	0.01W
Path Lost Model	Free Space Loss
Ranging Power	0.25 mW

Table 18. FAP (WiMAX) parameters

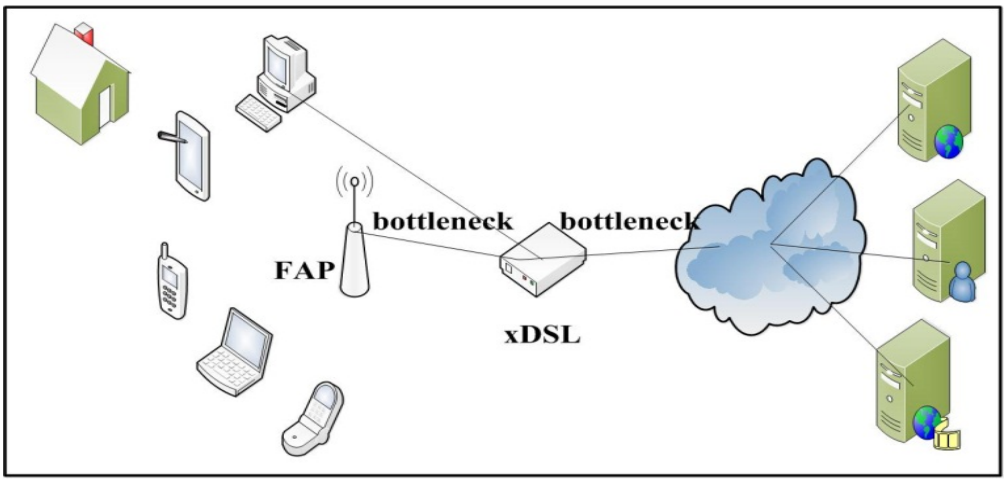


Figure 77. Network Architecture Model

As part of MAC layer's functions, scheduling is needed to handle resource allocation (transmit power, bandwidth, timeslot, etc.) and priority handling of data flows by considering the individual bandwidth requests and QoS requirements. Scheduling mechanism is expected to be dynamic, efficient, and aware of both channel and backhaul conditions. In this section, we are more focused on the backhaul capacity limitation and assume that the FAP is close enough to the UE, hence all UEs will maintain good channel quality levels with relatively low variation.

The approach of backhaul aware scheduling and uses the following provisions:

1. All DL/UL bandwidth requests (B_{req}) from FAP are calculated. At the same time the availability of backhaul link (B_{link}) for certain period is calculated.

2. Admission control will cooperate with schedulers to decide whether the UE request can be served.

3. If $B_{req} \leq B_{link}$, then the scheduler will run the existing BS schedulers as commonly used in WiMAX.

4. If $B_{req} > B_{link}$, means backhaul is in bottleneck conditions or the new UE request will potentially overload backhaul link (e.g., xDSL link); the backhaul aware scheduler will be used.

5. Admission control will treatment traffic classes and those will be scheduled using backhaul aware scheduling algorithm.

Based on B_{link} estimation result, the FAP may decide whether or not to admit a new bandwidth request. Bottleneck in backhaul can be imposed by the FAP itself. Thus, if the amount of backhaul bandwidth available is not sufficient to support a new session from a high priority services, the FAP can reduce the number of sessions from a lower priority service. The high priority service will be rejected if the average delay of packets is exceeding a specified threshold or if the requested bandwidth exceeds the available bandwidth.

In order to evaluate the model, the simulation was performed for 5 scenarios. Each scenario consists of combination of traffic types. The scenarios are displayed in the following table.

Scenario	HTTP	FTP	VoIP	VIDEO
Data	50%	50%	0%	0%
VoIP	0%	0%	100%	0%
Streaming	0%	0%	0%	100%
Mix I	50%	20%	30%	0%
Mix II	10%	30%	60%	0%

Table 19. Traffic Mix Type Scenarios

5.2.3.1 Analytical model

Packet flow is modeled as a continuous bit stream and the rate of each flow is known. Suppose the xDSL link capacity is B_{link}. N is the total packet flows which consists of real time flows (l) and non-real time flows (m). The scheduling considers the real time and non-real time flows in the queue and delay requirements of real-time flows to allocate bandwidth. When polled by the FAP, each UE will request bandwidth allocation with the amount based on average data rates required by each flow. Suppose B_{req} is the total requested bandwidth from real-time and non-realtime traffic flows:

$$B_{req} = \sum_{i=1}^{l} R_{i,RT} + \sum_{i=1}^{m} R_{i,NRT} \tag{60}$$

where $R_{i,RT}$ is average data rate of real time traffic flow *i* and $R_{i,NRT}$ is for non-real time flow. FAP provides bandwidth based on the aggregate bandwidth request from a single UE.

If bottleneck occurred or $B_{req} > B_{link}$, the scheduler should determine the fair rate for individual traffic flows. If we refer to WiMAX terminology, fair rate (f_{rate}) is simply calculated as:

$$f_{rate} = \sum_{i=1}^{N} \min(R_i, CIR) \le B_{link} - B_{curr\_load} \tag{61}$$

Fair rate function have solution unique and it can control traffic at FAP before send to the network, because with the fairness property can use its capacity to effectively bandwidth, its mean that class traffic which requires large bandwidth get bandwidth allocation more effective and efficient, mainly for real time traffics [Noviyanti 2010].

The Committed Information Rate (CIR) is defined for each QoS types (UGS, ertPS, rtPS, nrtPS, BE). For UGS traffic, CIR is equal to its maximum information rate (MIR), and for BE, the CIR is equal to zero. While for ertPS, rtPS and nrtPS the CIR refers to individual CIR provisioned (along with MIR) by the mobile operator. By using this information the fair rate can be determined and then required to update the labeling re-rate the new service with a new fair rate with $l_{new} = \min(l_{old}, f_{rate})$.

Backhaul bandwidth estimation is calculated based on utilization (U_{link}) reference in the backhaul network. For a period of t and (t + τ), BW_{link} is defined as follows:

$$B_{link} = C_{link}[1 - U_{link}(t, t+\tau)] \tag{62}$$

Based on (61) fair rate received by the user will be decisive for the FAP to be able to allocate the real time or non-real time services with treatment as follows;

If the load demands for real time service flows is greater than non-real time ones then the scheduler will prioritize a real time service, with the proportion based on dropping probability calculation and the amount of real time bandwidth request. It is expected that with this treatment in FAP, fairness for each service request is guaranteed.

5.2.3.2 Simulation Result

The following sub sections shows simulation results with xDSL Download speeds 2 Mbps and 3 Mbps on different traffic mix types scenarios

Scenario 1: Data

In this scenario, the traffic model consist of 50% HTTP and 50% FTP. The simulation results are shown in Figure 78.

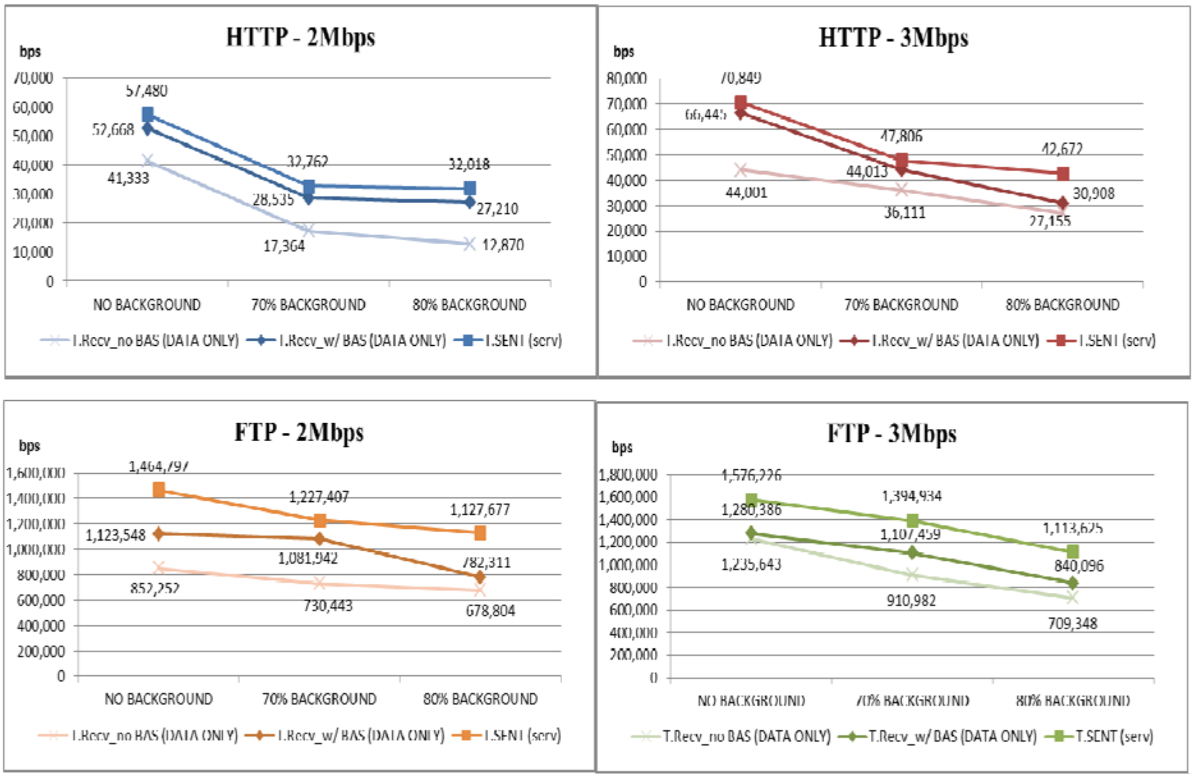


Figure 78. Scenario 1 Results: Traffic Type Data Throughput

For xDSL 2 utilizing Mbps, FAP with BAS shows the improvement in term of received data throughput compared to the non BAS one. For HTTP traffic, the improvements gained by the system are 8%, 13% and 15% respectively for 3 background data conditions (i.e., no background data, 70% background data and 80% background data). Whereas for FTP traffic, the improvements gained by the system are 23%, 12%, and 31% respectively for the same 3 background data conditions. For FAP without BAS, the received data throughput is reduced by 28%, 47%, and 60% for HTTP traffic and 42%, 40% and 40% for FTP traffic, each for the 3 background data conditions.

Results for xDSL with 3Mbps show the same characteristics. The improvements gained by the system are 6%, 8% and 28% respectively for 3 background data conditions. Whereas for FTP traffic, the improvements gained by the system are 19%, 21%, and 23% respectively for the same 3 background data conditions. For FAP without BAS, the received data throughput is reduced by 38%, 24%, and 26% for HTTP traffic and 22%, 35% and 36% for FTP traffic, each for the 3 background data conditions.

Results also show that the increased xDSL Download Rate from 2 Mbps to 3 Mbps, affects the improvement gained by the system, i.e., 5-6% for FTP traffic and 2% for HTTP traffic. Different results occurs for 80% background traffic in 3Mbps xDSL backhaul, which shows the reduction of HTPP traffic throughput compared to FTP traffic by 13%. This was caused by the system that has higher priority for FTP traffic compared to HTTP.

Scenario 2: VoIP

In this scenario, the traffic model consist of 100% VoIP generated by all four users. The simulation results are shown in Figure 79.

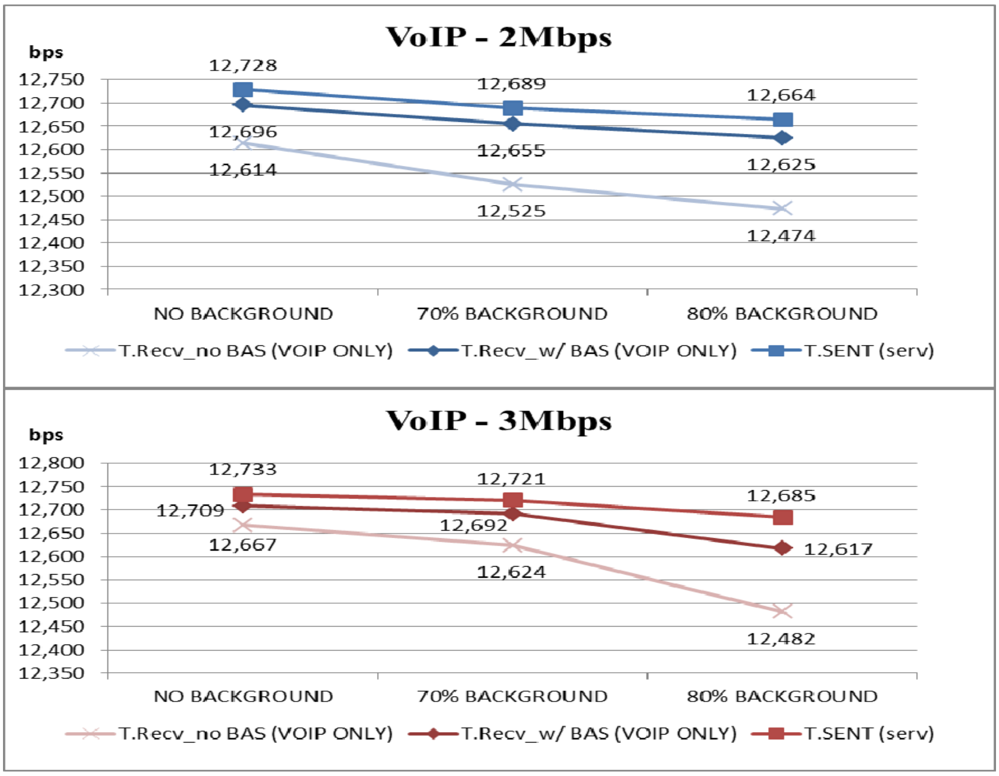


Figure 79. Scenario 2 Results: Traffic Type VoIP Throughput

For xDSL with connection speed equal to 2 Mbps, FAP with BAS shows the improvement in term of received data throughput compared to the non BAS one. The improvements gained by the system are 0.25%, 0.26% and 0.31% respectively for 3 background data. Whereas for FAP without BAS, the received data throughput is reduced by 0.9%, 1.2%, and 1.5% for individual background data conditions.

Results for xDSL 3Mbps shows the same characteristic. The improvements gained by the system are 0.19%, 0.22% and 0.53% respectively. On the other hand, for FAP without BAS, the received data throughput is reduced by 0.52%, 0.76%, and 1.6% each for the 3 background data conditions.

Scenario 3: Streaming

In this scenario, the traffic model consists of 100% streaming generated by all four users. The simulation results are shown in Figure 80.

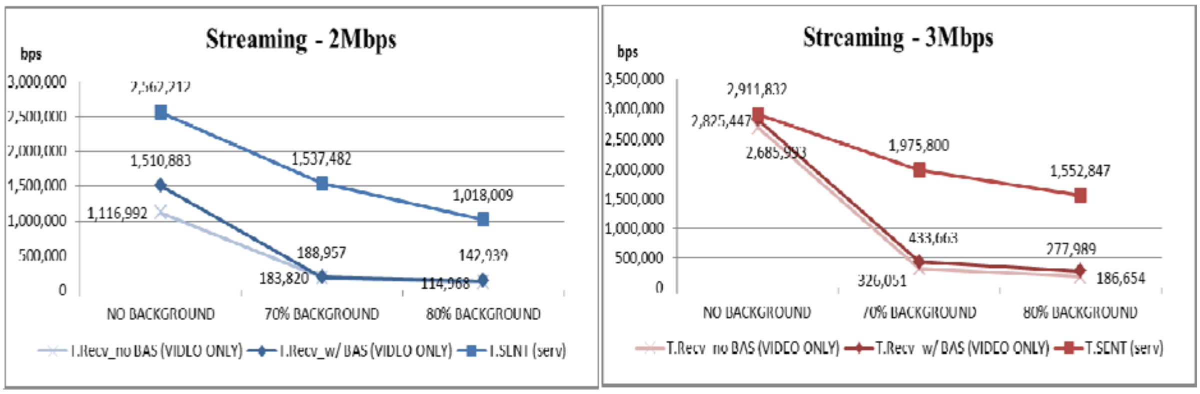


Figure 80. Scenario 3 Results: Traffic Type Streaming Throughput

For xDSL 2 Mbps, FAP with BAS shows significant reduction in term of received data throughput compared to the throughput of sent traffic, i.e., 41%, 88%, and 86% respectively for 3 background data conditions. Whereas for FAP without BAS, the received data throughput is reduced by 56%, 88%, and 89% for each background data conditions.

Results for xDSL 3Mbps shows improved performance compared to the 2 Mbps xDSL. The reductions of received data throughput are 3%, 78%, and 82% respectively. On the contrary, for FAP without BAS, the received data throughput is reduced by 8%, 83%, and 88% for the 3 background data conditions.

This condition occurs because all users simultaneously accessed the streaming application which has high priority, in the other hand; the bandwidth of backhaul link is limited, especially with 70% and 80% background traffic.

Scenario IV: Traffic Type MIX I

In this scenario, the traffic model consists of 50% HTTP, 20% FTP, and 30% VoIP generated by all four users. The simulation results are shown in Figure 81.

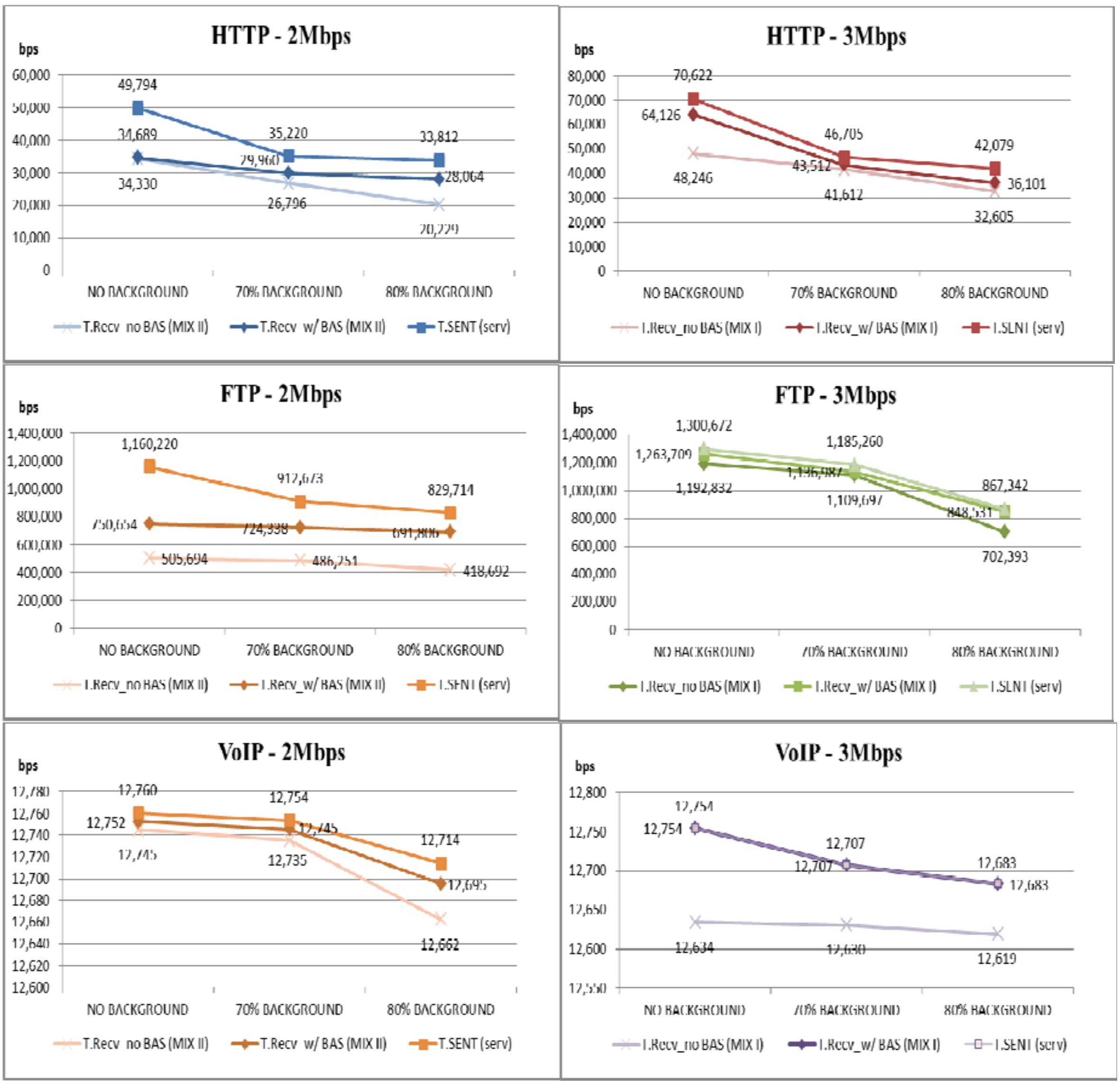


Figure 81. Scenario 4 Results: Traffic Type MIX I Throughput

For xDSL 2 Mbps, FAP with BAS shows the improvement in term of received data throughput compared to the non BAS one. For HTTP traffic, the improvements gained by the system are 30%, 15% and 17% respectively for 3 background data conditions. While for FTP traffic, the improvements gained by the system are 35%, 20%, and 16% respectively. For FAP without BAS, the received data throughput is reduced by 31%, 23%, and 40% for HTTP traffic and 57%, 47% and 50% for FTP traffic, each for the 3 background data conditions.

Results for xDSL 3Mbps shows the same characteristic. The improvements gained by the system are 9%, 7% and 14% respectively for 3 background data conditions. Whereas for FTP traffic, the improvements gained by the system are 3%, 4%, and 2% respectively for the same 3 background data conditions. For FAP without BAS, the received data throughput is reduced by 38%, 24%, and 26% for HTTP traffic and 8%, 6% and 19% for FTP traffic, each for the 3 background data conditions.

Results also show that the increased xDSL Download Rate from 2 Mbps to 3 Mbps, affect the improvement gained by the system, i.e., 5-6% for FTP traffic and 2% for HTTP traffic. Different results occurs for 80% background traffic in 3Mbps xDSL backhaul, which shows the reduction of HTPP traffic throughput compared to FTP traffic by 13%. This was caused by the system that has higher priority for FTP traffic compared to HTTP.

For VoIP traffic with xDSL 2 Mbps, FAP with BAS shows the improvement in term of received data throughput compared to the non BAS one. The improvements gained by the system are 0.06%, 0.06% and 0.15% respectively for 3 background data conditions. Whereas for FAP without BAS the received data throughput is reduced by 0.12%, 0.14%, and 0.41%, each for the 3 background data conditions.

Results for VoIP traffic with xDSL 3 Mbps shows that no reduction of throughput in received traffic from the sent one for all background data conditions. Whereas for FAP without BAS the received data throughput are reduced by 0.94%, 0.6%, and 0.15%, each for the 3 background data conditions.

Scenario V: Traffic Type MIX II

In this scenario, the traffic model consists of 10% HTTP, 30% FTP, and 60% VoIP generated by all four users. The simulation results are shown in Figure 82.

For xDSL 2 Mbps, FAP with BAS shows the improvement in term of received data throughput compared to the non BAS one. For HTTP traffic, the improvements gained by the system are 8%, 47% and 31% respectively for 3 background data conditions. Whilst for FTP traffic, the improvements gained by the system are 15%, 49%, and 45% respectively for the same 3 background data conditions. For FAP without BAS, e received data throughput is reduced by 14%, 61%, and 39% for HTTP traffic and 26%, 59% and 65% for FTP traffic, each for the 3 background data conditions.

Results for xDSL 3Mbps shows the same characteristic. The improvements gained by the system are 5%, 48% and 47% respectively for 3 background data conditions. Whereas for FTP traffic, the improvements gained by the system are 43%, 48%, and 32% respectively for the same 3 background data conditions. For FAP without BAS, the received data throughput is reduced by 12%, 52%, and 65% for HTTP traffic and 43%, 75% and 72% for FTP traffic, each for the 3 background data conditions.

For VoIP traffic with xDSL 2 Mbps, FAP with BAS shows the improvement in term of received data throughput compared to the non BAS one. The improvements gained by the system are 0.45%, 0.38% and 0.25% respectively for 3 background data conditions. Whereas for FAP without BAS the received data throughput is reduced by 0.52%, 0.46%, and 0.33%, each for the 3 background data conditions.

Results for VoIP traffic with xDSL 3 Mbps, FAP with BAS shows the improvement in term of received data throughput compared to the non BAS one. The improvements gained by the system are

0.31%, 0.3% and 0.52% respectively for 3 background data conditions. Whereas for FAP without BAS the received data throughput are reduced by 0.49%, 0.43%, and 0.57%, each for the 3 background data conditions.

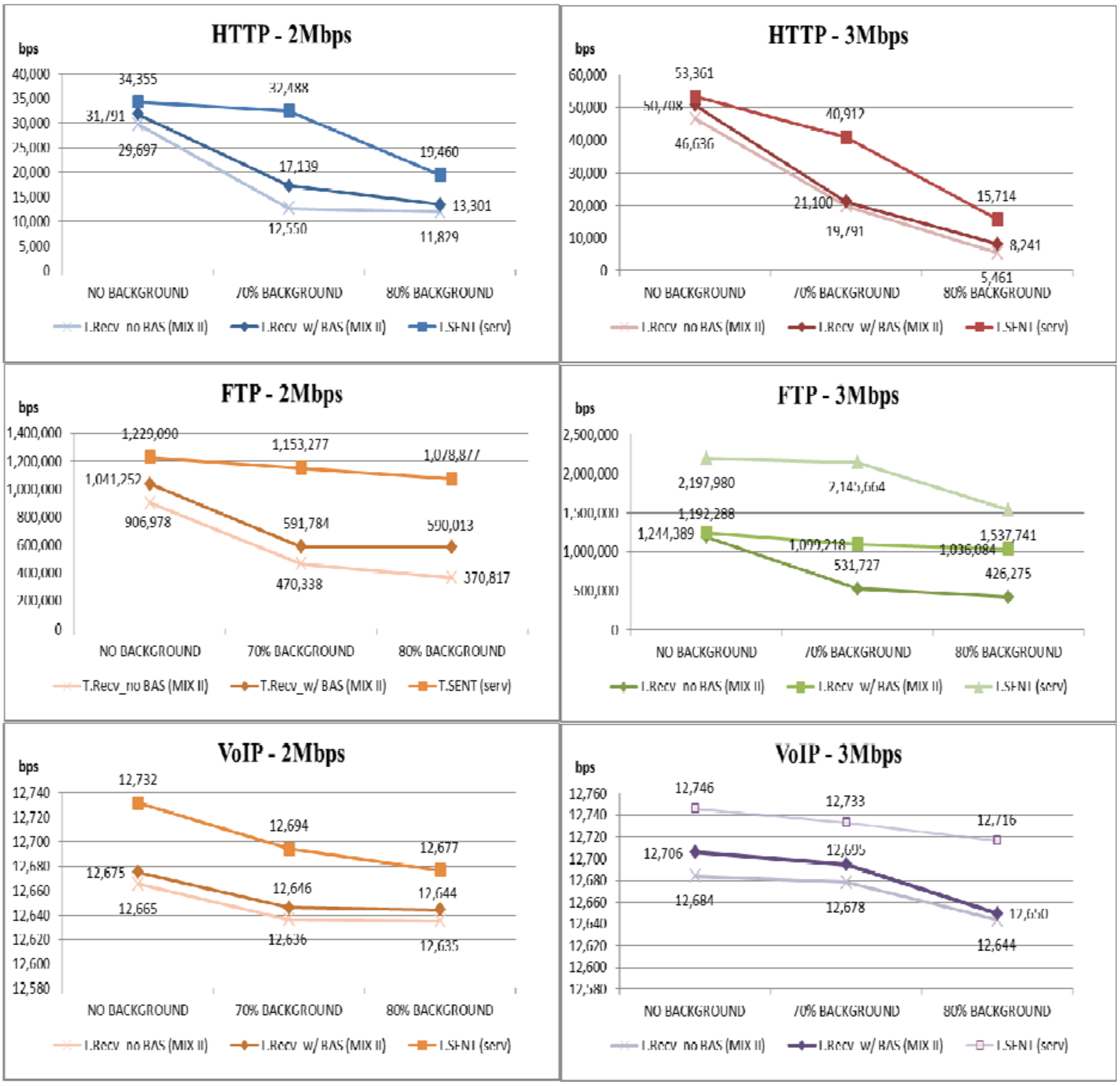


Figure 82. Scenario 5 Results: Traffic Type MIX II Throughput

5.2.3.3 Conclusion

From the performed simulation, some conclusions can be drawn as mention in the following remarks. In term of evaluating the performance of FAP with BAS, simulations demonstrate the ability of backhaul aware scheduling techniques to improve the throughput of received traffic. If the utilization of backhaul rises, it will significantly affect the received throughput of data. Admission control and BAS treatment can improve FAP performance for each traffic class. If the backhaul capacity is expanded (in this simulation from 2 Mbps to 3 Mbps) the FAP performance in serving of traffic can be improved.

6 CROSS-LAYER OPTIMIZATION

A fundamental problem in networking is to provide efficient resource allocation among the users in the system. On one hand, the scheduling algorithm has to prioritize the requests according to the user quality-of-service (QoS) requirements. On the other hand, the wireless channels offer *physical layer resources* lying in the frequency domain, time domain, and spatial domain, as well as combinations of thereof. Unlike the fixed wired network where the channel is time-invariant, wireless channels are time-varying. Hence, the conventional isolated design approach of optimizing the physical layer and the MAC layer separately (e.g. [Hajek98]) fails to exploit the dynamic nature of the physical layer and is suboptimal in multiuser wireless channels.

This motivates *cross-layer approaches* where the MAC layer and the physical layer are jointly optimized. In a cross-layer optimization design, there are two main challenges. The MAC layer scheduling algorithm must be adaptive to the dynamics of the system, which are contributed by the physical layer dynamics and the source statistics of the user applications. For instance, the MAC layer has to assign priority based on the channel conditions (the physical layer condition) and buffer occupancy (the source statistics) in the user queues to ensure that the user QoS requirements are satisfied and the resource utilization is maximized. To enable the design of a jointly adaptive MAC layer that can also provide a complete analysis of delay and throughput, we certainly require a cross-layer design framework that can adapt to both *source dynamics* and *physical layer dynamics*. In packet-based wireless data networks, variable sized packets for each user arrive at random instants in time. These data packets have to be sent over fading channels, generally in the presence of interference generated by simultaneous transmissions that share the same system resources. In this scenario the problem of designing a scheduling policy in the resources allocation is fundamental.

In this framework, we consider the problem of the optimal resources allocation in the downlink channel of an OFDMA femtocell network where FAPs share the same frequencies to transmit to their own users. According to a cross-layer approach each FAP has to allocate its resources in order to guarantee the stability of the queuing system composed by buffers where users packets are stored before their transmission. Because of the FAPvsFAP interference the scheduling strategies of the FAPs are not independent; we propose a distributed solution with no centralized control among the interfering FAPs. Due to the inherently competitive nature of this multi-cell system we formulate the system design within the convenient framework of Game Theory. The performance of OFDMA downlink channels, where without loss of generality the orthogonality is achieved in the frequency domain, have been analyzed for a large class of scheduling policies in several papers ([Yeah04], [Goyal02] [Cohen03]). However, the system model that all these works assume is composed of a single cell so that the inter-cell interference is not considered in the optimal scheduling problem.

The work is organized in the following way. First we describe the system model and formulate our problem using the Game Theory framework. Then after proposing a stabilizing power allocation policy we provide distributed algorithms able to reach the proposed solution. Finally we analyze their convergence conditions and global behavior.

6.1 System model

We consider downlink transmissions in a femtocell network composed by Q FAPs, sharing the same physical resources (i.e. time and frequency). So each FAP can interfere with all the FAPs in the network. Since our goal is to find distributed algorithms that do not require neither a centralized control nor coordination among different FAPs, we focus on transmission techniques where FAPvsFAP interference is treated by each FAP as additive, albeit colored, noise. Moreover, we assume that the transmissions towards FUEs within each femtocell are carried out over orthogonal subchannels.

As mentioned before, we consider in the following the use of OFDMA for the downlink transmissions within each cell. Then, the subcarrier-wise baseband model (after OFDMA modulation and demodulation) for a network composed by Q FAPs and N FUEs for each femtocell is:

$$\mathbf{y}(k) = \mathbf{H}(k)\mathbf{s}(k) + \mathbf{w}(k), \quad k \in \mathcal{N}, \tag{63}$$

where k denotes the subchannel index, $\mathcal{N} = \{1,\ldots,N\}$ is the number of active FUEs within each cell; $\mathbf{s}(k) = \{s_q(k)\}_{q\in\Omega}$ is a vector whose q-th entry is the information symbol transmitted from the FAP q to its FUE k, and $\Omega = \{1,\ldots,Q\}$ denotes the set of the FAPs; $\mathbf{y}(k) = \{y_q(k)\}_{q\in\Omega}$ is a vector defined similarly to $\mathbf{s}(k)$, but containing the received signals; $\mathbf{w}(k)$ is a zero mean circularly symmetric complex Gaussian white noise vector, whose q-th element has variance $\sigma^2_{w_q}(k) = E\left\{\left|w_q(k)\right|^2\right\}$; $\mathbf{H}(k)$ is the $Q \times Q$ channel matrix over subchannel k, $\left[\mathbf{H}(k)\right]_{rq} \triangleq \bar{H}_{rq}(k) / \sqrt{d^{\gamma}_{rq}}$, where $\bar{H}_{rq}(k)$ denotes the channel between FAP r and FUE k in the cell q, normalized by the path-loss d^{γ}_{rq} with exponent γ. Observe that the diagonal elements of $\mathbf{H}(k)$ contain the direct channels between each FAPs and its own k-th user, whereas the off-diagonal elements contains the cross-channels that generate the FAPvsFAP interference.

Given the I/O system in (63), we make the following assumptions:

- **A.1** Each channel changes sufficiently slowly so that it can be considered fixed during the whole transmission, so that the achievable rate is a meaningful performance indicator;

- **A.2** The channel from each FAP to its own destination is known to the intended receiver, but not to the other terminals; an error-free estimate of inter-cell interference is also supposed to be available at each receiver. Each user in the cell transmits this information back to its FAP through a low (error-free) bit rate feedback channel;

- **A.3** The subchannel distributions among the users (FUEs) in each cell is assumed to be given. Thus, the degree of freedom of each FAP is the power allocation among the users in the femtocell.

We consider the following power constraints. For each FAP q:

- **Co.1** Maximum overall transmit power:

$$E\left\{\left\|\mathbf{s}_q\right\|_2^2\right\} = \sum_{k\in\mathcal{N}} \bar{p}_q(k) \le NP_q, \tag{64}$$

where $\mathbf{s}_q$ contains the N symbols transmitted by the FAP q to the N FUEs in the cell, $\bar{p}_q(k) \triangleq E\left\{\left|s_q(k)\right|^2\right\}$ denotes the power allocated by FAP q for user k and P_q is total transmit power of FAP q, in units of energy per transmitted symbol.

- **Co.2** Peak power constraints:

$$E\left\{\left|s_q(k)\right|^2\right\} = \overline{p}_q(k) \leq \overline{p}_q^{\max}(k), \quad k \in \mathcal{N}, \tag{65}$$

where $\overline{p}_q^{\max}(k)$ represents the maximum power that is allowed to be transmitted on the *k*-th subchannel from FAP q.

It is worth pointing out that the overall system as given in (63) is equivalent to a Gaussian frequency-selective Interference Channel (IC) with Q links (the number of FAPs), each of them composed by N frequency-bins (the number of FUEs in the cell). It follows that the maximum achievable rate of each link in the IC, given the interference of the other links, corresponds to the maximum achievable sum-rate of the associated cell of the multicell cellular system, given the inter-cell interference due to the other cells. Figure **83** shows this correspondence for a two-cell cellular system. It turns out that all the results that we are going to present hereafter for the downlink scenario, also apply to this alternative setup.

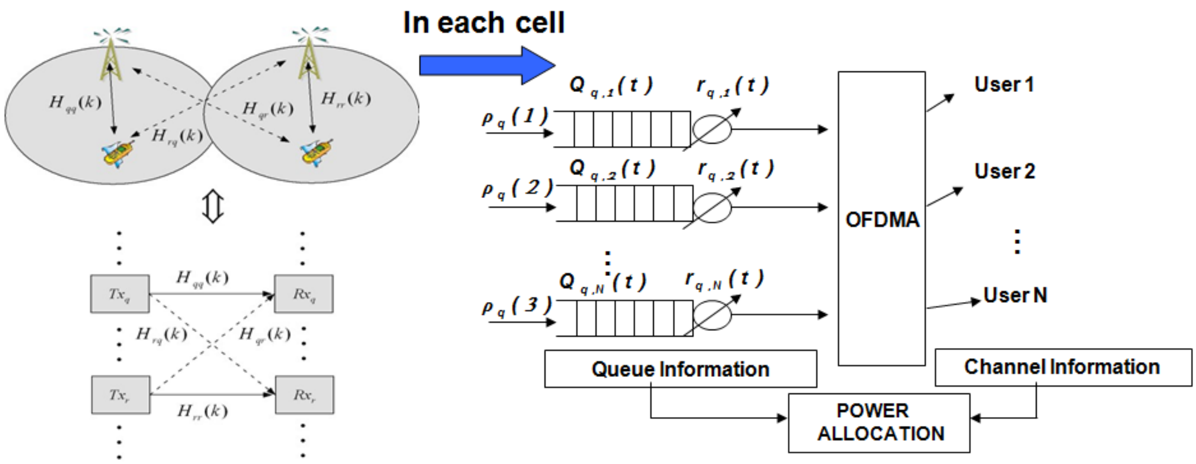


Figure 83. Multicell Cellular System as Frequency-Selective Interference Channel

At the FAP each user has a buffer into which its packets are stored until they are served by the FAP. The packets of the *k*-th user in the *q*-th cell arrive according to an ergodic account process $A_{q,k}(t)$, representing number of packet arrivals up to time t. The packet lengths for each user are independent identically distributed (i.i.d.) according to the distribution $\mathcal{F}_{Z_{q,k}}$ with $E[Z_{q,k}] < \infty$ and $E[Z_{q,k}^2] < \infty$. Let $\lambda_{q,k}$ and $Q_{q,k}(t)$ denote the packet arrival rate and the queue length of the *k*-th user in the *q*-th cell at the time instant *t*, respectively. We denote with $\rho_{q,k} = \lambda_{q,k} E[Z_{q,k}]$ the bit arrival rate of the *k*-th user in the *q*-th cell. Each FAP represents a queuing system characterized by a bit arrival rate vector

$$\rho_{\mathbf{q}} = [\rho_q(1), \ldots, \rho_q(N)], \quad q \in \{1, \ldots, Q\}. \tag{66}$$

The temporal axis of the system is divided in slots whose length is at most equal to the channels coherence time; in each time slot the FAP computes the optimal power allocation among the users in the cell. The queues temporal evolution is described by the following discrete dynamical equation:

$$Q_{q,k}(i+1) = \max(Q_{q,k}(i) + C_{q,k}(i) - r_{q,k}(i) * T, 0) \tag{67}$$

where i denotes the i-th time slot of length T, $C_{q,k}(i)$ the number of bits sent to the k-th user in the q-th cell that arrive in the slot i and $\mathrm{r}_{q,k}(i)$ is the maximum achievable rate of the k-th user in the q-cell in the time slot i.

6.2 Game theoretical formulation

According to the equivalence between the cellular system in Figure 83 and the IC and under **A.1**-**A.3**, the optimal resource allocation problem reduces then to finding the optimum power allocation for each FAP to maximize the sum of the information rates of all the FUEs in each cell weighted by their queues length, subject to global power and peak power constraints, and treating the FAPvsFAP interference as additive noise. The latter constraint is motivated by possible restrictions on the usage of certain frequency bands, in order to limit the amount of interference that each FAP can generate. This rate maximization problem is a multi-objective optimization problem as the weighted sum-rate achieved by each cell constitutes a different single objective. Hence it is convenient to formulate the system design under the framework of game theory. In particular, we formulate the weighted sum-rate maximization problem as a strategic non-cooperative game, where every FAP is a player that competes against the other FAPs by choosing the signaling and the power allocation that maximizes its own sum-rate. An equilibrium for the whole system is reached when every player is unilaterally optimum, i.e., when, given the current strategies of the others, any change in its own strategy would result in a rate loss. This equilibrium constitutes the celebrated notion of Nash Equilibrium (NE) in game theory.

In the next sections we provide conditions for the existence and the uniqueness of NE. Then we will find distributed algorithms to reach this NE. Finally we give sufficient conditions for the convergence of the proposed schemes. However, we first need to state some preliminary definitions

6.3 Weighted Sum-Rate Maximization Game

Given the system model in Figure 83 and the assumptions **A.1**-**A.3**, the problem becomes then to find the optimal power allocations for each FAP in the presence of FAPvsFAP interference, subject to the constraints **Co.1**-**Co.2**, that guarantees the stability of the queuing system. As in [Neely02], we say the system is stable under a certain scheduling policy if:

$$\Psi_{q,k}(\xi) = \limsup_{t\to\infty} \int_0^t \mathbf{1}_{[Q_{q,k}(\tau)>\xi]} d\tau \to 0 \tag{68}$$

as $\xi \to \infty$ for all the queues, i.e. $\forall q \in \{1,\ldots,Q\}$and $\forall k \in \{1,\ldots,N\}$. It is clear that the queuing system cannot be stabilized for any bit arrival rate vector $\boldsymbol{\rho}$; as a consequence we can introduce the definition of stability region.

Definition 1 :*. The* ***stability region*** *is the set of all the bit arrival rate vector* $\boldsymbol{\rho}$ *for which there exist a scheduling policy that makes the system stable.*

Hence given a bit arrival rate vector $\boldsymbol{\rho}$ in the stability region, there exist a scheduler able to stabilize the queuing system, but not all the schedulers make the system stable.

***Definition 2:**. A scheduler is **throughput optimal** if it stabilizes the queuing system without knowing the bit arrival rate vector $\boldsymbol{\rho}$ as long as $\boldsymbol{\rho}$ is within the system's stability region.*

A cross-layer optimization requires that the power allocation among the users in each cell be chosen according to some *throughput optimal* scheduling strategy. Because of the FAPvsFAP interference the optimal scheduling strategy in each cell depends on the power allocations used by the other FAPs.

Hence, to compute the globally optimal power allocation for all the FAPs, a centralized control that solves the non-convex optimization problem is required. Since the FAPs are not co-located, a centralized solution that requires exchange of signaling among the cells cannot in general be implemented. Thus, we focus on non cooperative solutions based on distributed algorithms that do not require any coordination among different FAPs. Such a solution is suitable when the backhaul link is not available or its quality is not good enough to guarantee a reliable exchange of information.

This approach is generally sub-optimal, i.e. it does not guarantee the stability of the queuing system in each cell for all the possible bit arrival rates in the stability region, but it has the great advantage of not requiring any coordination and signaling among interfering FAPs.

There exist a wide class of scheduling strategies that are throughput optimal. In this report we consider the Max-Weight scheduler, as defined next.

***Definition 3:** At any time slot of scheduling t, the **Max-Weight scheduler** allocates resources among the users in order to maximize*

$$\max_{\mathbf{r}(t)\in C(t)} \sum_{i=1}^{N} Q_i(t) r_i(t) \tag{69}$$

where $\mathbf{Q}(t) = [Q_1(t),\dots,Q_N(t)]$ is the vector of the queue length of the users and $\mathbf{r}(t) = [r_1(t),\dots,r_N(t)]$ is the data rate vector within the instantaneous feasible capacity region $C(t)$ in the physical layer.

Let $\mathbf{p}_q(t) \doteq [p_q(1,t),\dots,p_q(N,t)]$ denote the power allocation chosen by the q-th FAP in the time slot t. In order to emulate a Max-Weight scheduler each FAP in any time slot, i.e. for any given channels realization and FAPvsFAP interference pattern, chooses $\mathbf{p}_q(t)$ in order to maximize

$$\begin{aligned} &\max_{\mathbf{r}(t)\in C(t)} \sum_{i=1}^{N} Q_i(t) r_i(t) \\ &s.t. \\ &\sum_{k=1}^{N} p_q(k,t) \le P_q \end{aligned} \tag{70}$$

where $Q_{q,k}(t)$ is the queue length of the k-th user in the q-th cell at the beginning of the time slot t. $SR_q^w(t)$ represents the sum-rate weighted by the queues achieved by the q-th FAP in the time slot t.

Now, given the signal model in (63), the achievable weighted sum-rate for each cell q is computed as the maximum weighted sum-rate in the cell, treating from each receiver the FAPvsFAP as additive noise. It is straightforward to see that a NE is obtained if each FAP transmits using Gaussian signaling, with a proper power allocation. In fact, for each FAP, given that all other FAPs use Gaussian codebooks, the optimal codebook maximizing the sum-rate is also Gaussian [Tse05].

Hence, the maximum achievable pay-off for the q-th FAP is given by:

$$SR_q = \sum_{k=0}^{N-1} Q_{q,k} \log\left(1 + \mathsf{sinr}_q(k)\right), \tag{71}$$

with $\mathsf{sinr}_q(k)$ denoting the Signal-to-Interference plus Noise Ratio (SINR) of the k-th user in the q-th cell:

$$\mathsf{sinr}_q(k) \triangleq \frac{\left|\bar{H}_{qq}(k)\right|^2 \bar{p}_q(k) / d_{qq}^{\gamma}}{\sigma_{w_q}^2(k) + \sum_{r \neq q} \left|\bar{H}_{rq}(k)\right|^2 \bar{p}_r(k) / d_{rq}^{\gamma}} \triangleq \frac{\left|H_{qq}(k)\right|^2 p_q(k)}{\sigma_{w_q}^2(k) + \sum_{r \neq q} \left|H_{rq}(k)\right|^2 p_r(k)}, \tag{72}$$

where

$$H_{rq}(k) \triangleq \bar{H}_{rq}(k) \sqrt{\frac{P_r}{d_{rq}^{\gamma}}}, \tag{73}$$

and $p_q(k) \triangleq \bar{p}_q(k) / P_q$ is the normalized power allocated by the q-th FAP for the k-th user.

Observe that in the case of practical coding schemes, where only finite order constellations can be used, we can use the gap approximation analysis and write the number of bits transmitted over the N substreams from the q-th FAP still as in (71) (for a given family of constellations and a given error probability $P_{e,q}$), simply replacing $\left|H_{qq}(k)\right|^2$ in (72) with $\left|H_{qq}(k)\right|^2 / \Gamma_q$, where $\Gamma_q \geq 1$ is the gap. It depends only on the family of constellation and on $P_{e,q}$; for M-QAM constellations, for example, if the symbol error probability is approximated by

$$P_{e,q}(\mathsf{sinr}_q(k)) \approx 4\mathcal{Q}\left(\sqrt{(3/(M-1))\mathsf{sinr}_q(k)}\right), \tag{74}$$

the resulting gap is

$$\Gamma_q = (\mathcal{Q}^{-1}(P_{e,q} / 4))^2 / 3 \tag{75}$$

In summary, we have the following structure for the game:

$$\mathcal{G} = \{\Omega, \{\mathcal{P}_q\}_{q \in \Omega}, \{SR_q\}_{q \in \Omega}\} \tag{76}$$

where $\Omega \triangleq \left\{1, 2, \ldots, Q\right\}$ denotes the set of the active links, $\mathcal{P}_q$ is the set of admissible (normalized) power allocation strategies, across the N subchannels, for the q-th FAP, defined as

$$\mathcal{P}_q \triangleq \left\{ \mathbf{p}_q \in \mathbb{R}^N : \frac{1}{N}\sum_{k=1}^{N} p_q(k) = 1, \quad 0 \le p_q(k) \le p_q^{\max}(k), \quad k = 1,\ldots,N \right\}, \tag{77}$$

with $p_q^{\max}(k) \triangleq \overline{p}_q^{\max}(k) / P_q$ and SR_q is the payoff function of the q-th player, defined in (71).

The optimal strategy for the q-th player, given the power allocation of the others, is then the solution to the following maximization problem:

$$\begin{aligned} &\max_{\mathbf{p}_q} \frac{1}{N}\sum_{k=1}^{N} Q_{q,k} \log\left(1 + \mathsf{sinr}_q(k)\right) \\ &s.t. \\ &\mathbf{p}_q \in \mathcal{P}_q \qquad \forall q \in \Omega \end{aligned} \tag{78}$$

where $\mathsf{sinr}_q(k)$ and $\mathcal{P}_q$ and are given in (72) and (77), respectively. Note that, for each q, the maximum in (78) is taken over $\mathbf{p}_q$, for a *fixed* $\mathbf{p}_{-q} \triangleq \left(\mathbf{p}_1,\ldots,\mathbf{p}_{q-1},\mathbf{p}_{q+1},\ldots,\mathbf{p}_Q\right)$.

The solutions of (78) are the well-known Nash Equilibria, which are recalled in the following.

A strategy profile $\mathbf{p}^{\Leftarrow} = \left(\mathbf{p}_1^*,\ldots,\mathbf{p}_Q^*\right) \in \mathcal{P}_1 \times \ldots \times \mathcal{P}_Q$ *is a Nash Equilibrium of the game* $\mathcal{G}$ *in* (78) *if*

$$\begin{aligned} &SR_q(\mathbf{p}_q^{\Leftarrow}, \mathbf{p}_{-q}^{\Leftarrow}) \ge SR_q(\mathbf{p}_q, \mathbf{p}_{-q}^{\Leftarrow}), \\ &\forall \mathbf{p}_q \in \mathcal{P}_q, \ \forall q \in \Omega. \end{aligned} \tag{79}$$

6.4 Nash Equilibria: Existence and uniqueness

According to $\mathcal{G}$, all the NEs of the game, if they exist, must satisfy the modified waterfilling solution for each user, i.e. the following system of nonlinear equations:

$$\mathbf{p}_q^{\Leftarrow} = \mathsf{WF}_q\left(\mathbf{p}_1^{\Leftarrow},\ldots,\mathbf{p}_{q-1}^{\Leftarrow},\mathbf{p}_{q+1}^{\Leftarrow},\ldots,\mathbf{p}_Q^{\Leftarrow}\right) = \mathsf{WF}_q(\mathbf{p}_{-q}^{\Leftarrow}) \ , \quad \forall q \in \Omega, \tag{80}$$

with the waterfilling operator $\mathsf{WF}_q\left(\cdot\right)$ defined as

$$\left[\mathsf{WF}_q\left(\mathbf{p}_{-q}\right)\right]_k \triangleq \left[Q_{q,k} - \frac{\sigma_{w_q}^2(k) + \sum_{r \ne q} \left|H_{rq}(k)\right|^2 p_r(k)}{\left|H_{qq}(k)\right|^2} \right]_0^{p_q^{\max}(k)} , \quad k \in \mathcal{N}, \tag{81}$$

where $\left[x\right]_a^b$ denotes the Euclidean projection of x onto the interval $[a,b]$.

The water-level μ_q is chosen to satisfy the power constraint $(1/N)\sum_{k=1}^{N} p_q^{\leftleftarrows}(k) = 1$. Given this nonlinear system of equations, the fundamental points are then:

a. Existence of the solution (NE);
b. Uniqueness of NE;
c. Designing distributed schemes to reach NE;

Before providing the conditions for the existence and uniqueness of the NE of game $\mathcal{G}$ we introduce the following intermediate definitions. Given game $\mathcal{G}$, define $\mathbf{S}(k) \in \mathbb{R}^{Q \times Q}$ as

$$\left[\mathbf{S}(k)\right]_{qr} \triangleq \begin{cases} \dfrac{|\bar{H}_{rq}(k)|^2}{|\bar{H}_{qq}(k)|^2} \dfrac{d_{qq}^{\alpha}}{d_{rq}^{\alpha}} \dfrac{P_r}{P_q}, & \text{if } k \in \mathcal{D}_q \cap \mathcal{D}_r \text{ and } r \neq q, \\ 0, & \text{otherwise,} \end{cases} \tag{82}$$

where $\mathcal{D}_q$ denotes the set $\{1,\ldots,N\}$ deprived of the subchannel indices that FAP q would never use as the best response set to any strategy used by the other FAPs, for the given set of transmit power and propagation channels:

$$\mathcal{D}_q \triangleq \left\{ k \in \{1,\ldots,N\} : \exists \mathbf{p}_{-q} \in \mathcal{P}_{-q} : \left[\mathsf{WF}_q\left(\mathbf{p}_{-q}\right)\right]_k \neq 0 \right\}, \tag{83}$$

with $\mathcal{P}_{-q} \triangleq \mathcal{P}_1 \times \cdots \times \mathcal{P}_{q-1} \times \mathcal{P}_{q+1} \times \cdots \times \mathcal{P}_Q$.

The study of game $\mathcal{G}$ is addressed in the following theorem, proved in [Scutari08b].

Theorem 1: *Game $\mathcal{G}$ a nonempty solution set for any set of channels, peak constraints and transmit power of the FAPs. Furthermore, the NE is unique if*

$$\rho\left(\mathbf{S}(k)\right) < 1, \qquad \forall k \in \{1,\ldots,N\}, \tag{84}$$

where $\mathbf{S}(k)$ is defined in (82) and $\rho\left(\mathbf{S}(k)\right)$ denotes the spectral radius of $\mathbf{S}(k)$.

We provide now alternative sufficient conditions for (84). To this end, we first introduce the matrix $\mathbf{S}^{\max} \in \mathbb{R}^{Q \times Q}$, defined as

$$\left[\mathbf{S}^{\max}\right]_{qr} \triangleq \begin{cases} \Gamma_q \max\limits_{k \in \mathcal{D}_q \cap \mathcal{D}_r} \dfrac{|\bar{H}_{rq}(k)|^2}{|\bar{H}_{qq}(k)|^2} \dfrac{d_{qq}^{\alpha}}{d_{rq}^{\alpha}} \dfrac{P_r}{P_q}, & \text{if } r \neq q, \\ 0, & \text{otherwise,} \end{cases} \tag{85}$$

with the convention that the maximum in (85) is zero if $\mathcal{D}_q \cap \mathcal{D}_r$ is empty. Then, we have the following corollary of Theorem 1.

Corollary 1: *A sufficient condition for* (84) *is:*

$$\rho\left(\mathbf{S}^{\max}\right) < 1 \tag{86}$$

where $\mathbf{S}^{\max}$ *is defined in* (85).

6.5 Distributed algorithms: Asynchronous Iterative Waterfilling Algorithm

The NE points of the game $\mathcal{G}$ can be computed using a distributed iterative weighted waterfilling procedure, proposed in [Scutari04] and called asynchronous weighted Iterative WaterFilling Algorithm, which is an instance of the totally asynchronous scheme of [Bertsekas08]. In the asynchronous IWFA, all the players maximize their own rate in a totally asynchronous way via the single user modified waterfilling solution. According to this asynchronous procedure, some FAPs are allowed to update their strategy more frequently than the others, and they might perform these updates using outdated information on the interference caused from the other FAPs. We show in the following that, whatever the asynchronous mechanism is, such a procedure converges to a stable NE of the game $\mathcal{G}$ under mild conditions on the FAPvsFAP interference.

In order to provide a formal description of the asynchronous IWFA, we need some preliminary definitions, as we introduce next. We assume, without loss of generality, that the set of times at which one or more FAPs update their strategies is the discrete set

$$T = \mathbb{N}_+ = \left\{0,1,2,\ldots\right\}. \tag{87}$$

Let $\mathbf{p}_q^{(n)}$ denote the power allocation of FAP q at the n-th iteration, and let $T_q \subseteq T$ denote the set of times n at $\mathbf{p}_q^{(n)}$ is updated (thus, at time $n \notin T_q, \mathbf{p}_q^{(n)}$ is left unchanged). Let $\tau_r^q(n)$ denote the most recent time at which the interference from FAP *r* is perceived by FUE in the cell *q* at the *n*-th iteration (observe that $\tau_r^q(n)$ satisfies $0 \leq \tau_r^q(n) \leq n$). Hence, if FAP q updates its power allocation at the *n*-th iteration, then it waterfills, according to (81), the interference level caused by

$$\mathbf{p}_{-q}^{(\tau^q(n))} \triangleq \left(\mathbf{p}_1^{(\tau_1^q(n))},\ldots,\mathbf{p}_{q-1}^{(\tau_{q-1}^q(n))},\mathbf{p}_{q+1}^{(\tau_{q+1}^q(n))},\ldots,\mathbf{p}_Q^{(\tau_Q^q(n))}\right). \tag{88}$$

The overall system is said to be totally asynchronous if the following weak assumptions are satisfied for each q ([Bertsekas08]):

$$\begin{aligned}
&\text{B1.} \quad 0 \leq \tau_r^q(n) \leq n,\\
&\text{B2.} \quad \lim_{k\to\infty} \tau_r^q(n_k) = +\infty,\\
&\text{B3.} \quad \left|T_q\right| = \infty.
\end{aligned} \tag{89}$$

where $\{n_k\}$ is a sequence of elements in T_q that tends to infinity. Assumption B1, B2 and B3 are standard in asynchronous convergence theory, and they are fulfilled in any practical implementation. In fact, B1 simply indicates that, in the current iteration *n*, each FAP *q* can use only interference vectors $\mathbf{p}_{-q}^{(\tau^q(n))}$ allocated by others FAPs in previous iterations (to preserve causality). Assumption B2 states that, for any given iteration index n_1, values of the components of $\mathbf{p}_{-q}^{(\tau^q(n))}$ in (88) generated prior to n_1, will not be used in the updates of $\mathbf{p}_q^{(n)}$ after a sufficiently long time n_2 which guarantees that old information is eventually purged from the system. Finally, assumption B3 indicates that no user fails to update its own strategy as time *n* goes on.

Using the above notation, the asynchronous IWFA is described in Algorithm 1.

Algorithm 1: *Asynchronous Iterative Waterfilling Algorithm*

1. Set $n = 0$ and $\mathbf{p}_q^{(0)}$ any feasible power allocation;

2. for $n = 0$: Number of iterations

$$\mathbf{p}_q^{(n+1)} = \begin{cases} \mathsf{WF}_q\left(\mathbf{p}_1^{(\tau_1^q(n))},\ldots,\mathbf{p}_{q-1}^{(\tau_{q-1}^q(n))},\mathbf{p}_{q+1}^{(\tau_{q+1}^q(n))},\ldots,\mathbf{p}_Q^{(\tau_Q^q(n))}\right), & \text{if } n \in T_q, \\ \mathbf{p}_q^{(n)}, & \text{otherwise;} \end{cases} \quad \forall q \in \Omega$$

3. end

Theorem 2: *The asynchronous weighted IWFA, described in Algorithm 1, converges to the unique NE of the game* $\mathcal{G}$ *in* (76) *if condition* (84) *holds.*

6.6 Numerical Results

In order to evaluate the performance of the proposed solution we consider a network scenario composed by different numbers of FAPs randomly distributed over a square area. The fading state remains constant for a period of *T* seconds, and then changes to a new independent fading state. The statistic of the channel fading is Rayleigh. The packet arrival process at each FAP is modeled as independent Poisson and packet lengths are i.i.d. exponential with a mean normalized respect to the user bandwidth equal to one. For the sake of simplicity, we assumed the same maximum transmit power for each FAP, i.e. $P_q = P_T$. The path-loss exponent is 3.5 and the SNR is defined respect to the total available power at the FAP. We compare the achieved results to those of two extreme cases.

The first one is the case of no FAPvsFAP interference to which the best possible achievable results are associated. The second one is the case of no signaling feedback from the users to the FAPs, i.e., the FAPs know neither the channels nor the interference variances. In this case all that the FAPs can do is to allocate uniformly the available power. Figure **84** shows an example of this comparison (the number of the users *N* served in each femtocell is 6); in this figure the red line denotes the results achieved with the proposed solution based on Game Theory, the blue line is the case of no FAPvsFAP interference and the black one is the case of uniform power allocation. From Figure **84** we can observe that the proposed algorithm based on game theory is able to serve traffic data with arrival rates higher the largest arrival rates that can be served with a uniform power allocation. Figure **85** represents the total average queue size vs. the packet arrival rate obtained using the game-theoretic approach, for different values of the interfering cells number *Q*; the number of users in each femtocell *N* = 6 and SNR = 15dB. From Figure **85**, we can see that the game-theoretic approach is able to work even with different numbers of interfering FAP's, of course with a loss in terms of the maximum arrival rate that can be served. In Figure **86** the total average queue size vs. the packet arrival rate is reported for different values of the number of users in each femtocell *N*; the interfering FAP number is *Q* = 3 and SNR = 15dB.

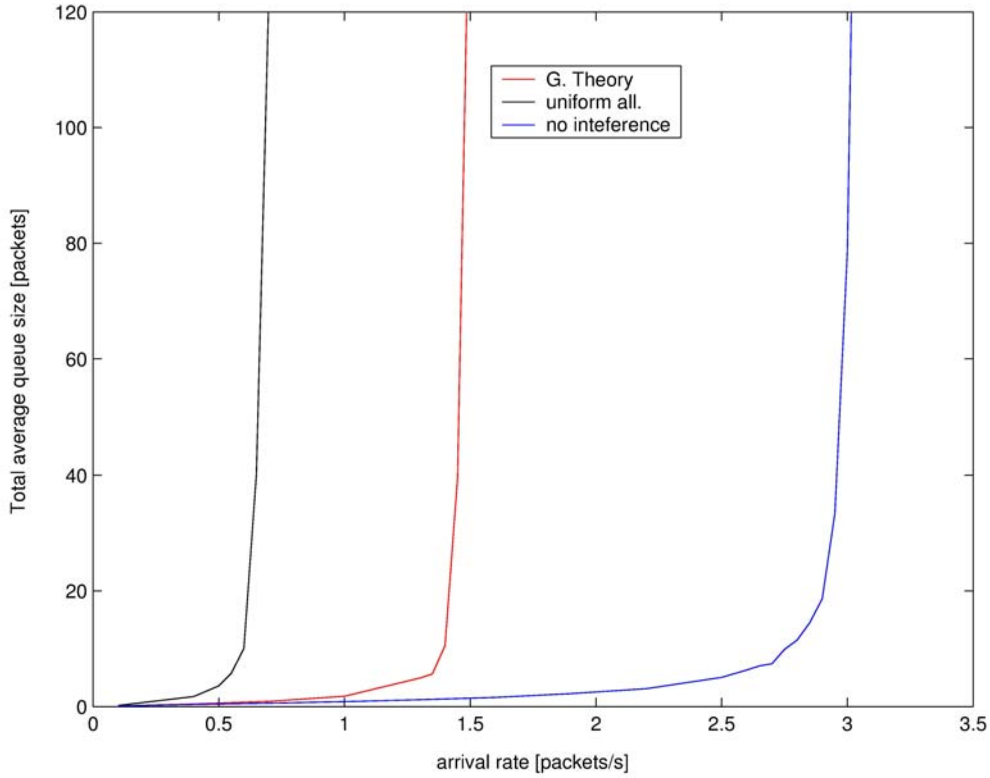


Figure 84. Total average queue size vs. arrival rate for *Q* = 3 and SNR =15dB.

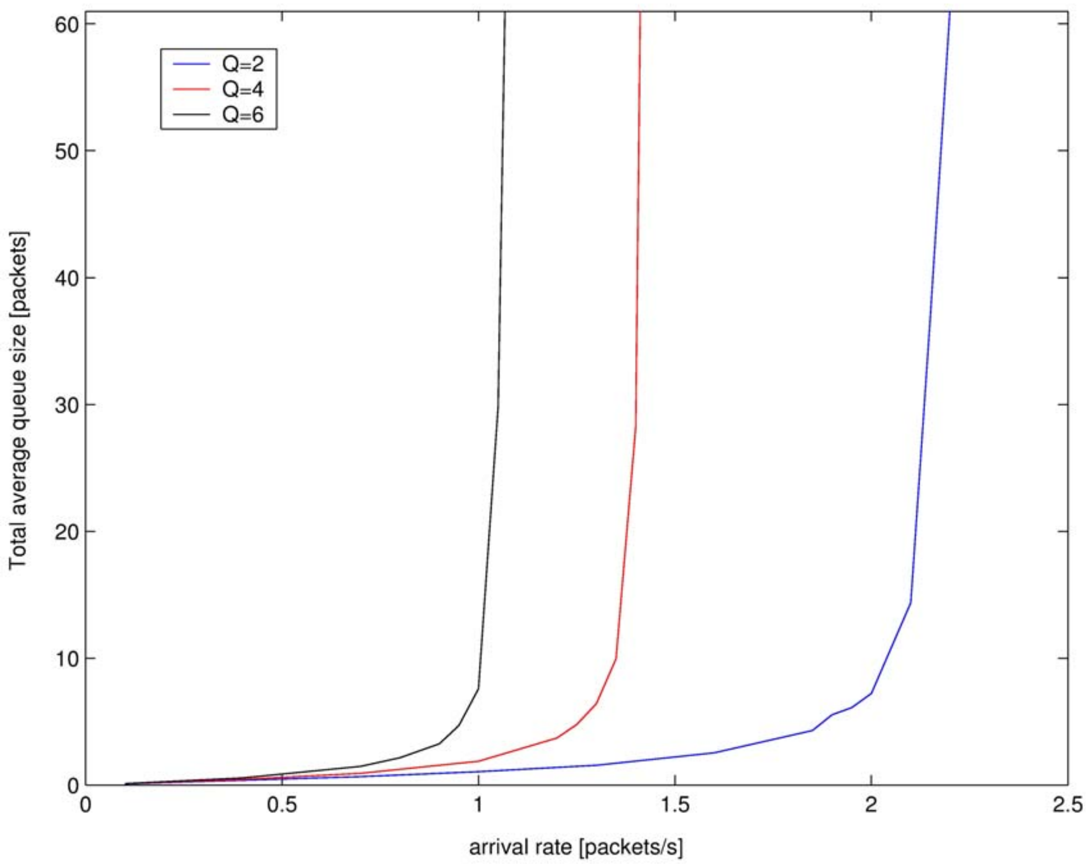


Figure 85. Total average queue size vs. arrival rate for different values of *Q*

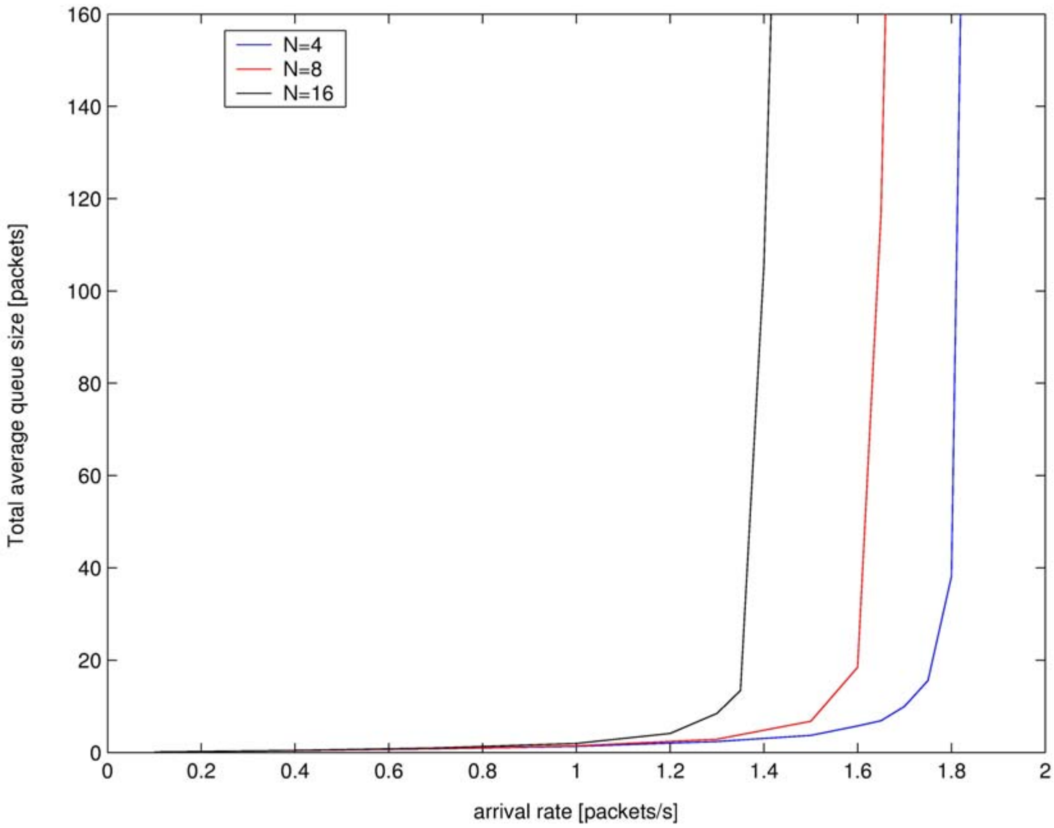


Figure 86. Total average queue size vs. arrival rate for different values of *N*

6.7 Conclusions

In this section we have considered the problem of the optimal resources allocation in the downlink channel of an OFDMA femto network. Following a *cross-layer* approach, each FAP has to allocate its resources in order to guarantee the stability of the queuing system composed by buffers where users packets are stored before their transmission. Because of the FAPvsFAP interference the scheduling strategies of the FAPs are not independent, hence we propose a distributed solution exploiting the convenient framework of Game Theory. According to this framework, every FAP allocates its power/bits as a best response to other FAPs scheduling. We have shown that, given a feasible set of arrival rates, the queues' stability is guaranteed if each FAP allocates its power/bits in order to maximize the weighted sum-rate (i.e. the rate weighted by the length of the arriving queues over each subcarrier). The solution, which can be found in a closed form, is a multi-level waterfilling, where the water level depends on the queue length. Finally we have shown by simulation that the game admits a stable Nash equilibrium, that is, an equilibrium where exists a set of arrival rates for which the queues' length maintains finite. The interesting result is that the proposed cross-layer approach that takes into account the queue length, the channel status and the interference level, is able to serve larger arrival rates with respect to the uniform power allocation case.

7 IMPLEMENTATION REQUIREMENTS AND COMPLEXITY OF PROPOSED PROCEDURES

Technical contribution	Enhancements required in LTE		Enhancements required in WiMAX	
	PHY layer	MAC layer	PHY layer	MAC layer
Routing **(CTU)**	• No modifications are needed at PHY layer. Only channel estimation of individual path has to be done in the same way as in conventional way	• Implementation of new MAC management messages to select appropriate path • Implementation of routing metric	• No modifications needed analogically to LTE	• The same modifications as in LTE, procedure is independent on access technology
Fast power control **(CTU)**	• No modifications needed as the measurement of channel quality is done in conventional LTE systems	• None special requirements at MAC layer	• No modifications needed analogically to LTE	• No modifications needed analogically to LTE as the procedure is independent on access technology
MBMS **(TELKOM)**	• None	• E-MBMS in femtocell, and compare transmission mode of PtP, PtM and SFN.	• None	• Generally the same principle as LTE but different terminology
Identification **(CTU)**	• Dynamic change of PSS and SSS location within PRB has to be assured	• A new management message to support handover FAP-MBS • A new management message to request PCI(s) of neighboring FAP(s) • Standard should support transmission of message about number of FAP clusters in a macrocell via BCH and backbone • Standard should support	• Not applicable, as this algorithm is specifically designed for LTE.	• Not applicable, as this algorithm is specifically designed for LTE

		transmission of list of neighboring FAPs besides the target FAP.		
Visiting UE **(CTU)**	• None	• New management messages for negotiation of the Visiting UE access • New flag introduced in request for enter CSG FAP	• None	• No modifications needed analogically to LTE as the procedure is independent on access technology
Authorization **(CTU)**	• None	• New order of management messages (consisting from old one) for access to CSG cell.	• None	• Not applicable for WiMAX as the procedure is designed specifically for LTE systems
Algorithms based on the exchange of interference pricing for precoder design **(UPC)**	• For every PRB and each direct channel eigenmode, the standard should support channel Vector Quantization reporting, along with a real number that represents the SNIR measured at each channel eigenmode. • For every PRB, the standard should support channel Vector Quantization for each eigenmode of the channel with dominant interferers, along with a real number that represents the amplitude of each channel eigenmode.	• X2 extension for communication between FAPs is required • X2 should support the transmission of information covering resource allocated for the protected measurement within the frequency channel. • It is necessary to define the information elements for distributing the "interference cost" over X2 interface per PRB (a proposal has been included in this deliverable)	• Same as for LTE	• Same as for LTE

	• The standards should support the calculation and reporting of the “interference sensitivity”			
LTE-A adapted pricing mechanisms for MCS and bandwidth part selection **(UPC)**	• The standards should support the calculation of the “interference sensitivity”. • The standards should support the measurement of the interference power from a single transmission. • The Uu interface should support the transmission of the interference cost per bandwidth part, per transmission layer, and per each dominant interferer	• X2 extension for communication between FAPs is required • X2 should support the transmission of information covering resource allocated for the protected measurement within the frequency channel. • It is necessary to define the information elements for distributing the “interference cost” over X2 interface per bandwidth part (a proposal has been included in this deliverable)	• Not applicable, as this algorithm is specifically designed for LTE.	• Not applicable, as this algorithm is specifically designed for LTE
Timer based interference mitigation **(CEA)**	• None	• Introduction of new commands from MBS to FAPs for forbidding frequency resources	• None	• No modifications needed analogically to LTE as the procedure is independent on access technology
Backhaul aware scheduling **(Telkom)**	• None	• Introduction of backhaul aware scheduling model to manage the performance of FAP in case of non perfect backhaul	• None	• No modifications needed analogically to LTE as the procedure is independent on access technology
Cross layer optimization	• A preliminary set-up phase is required at the beginning of each	• The scheduler must estimate the stability region in order set up	• Same as LTE	• Same as LTE

(UDSRLS)	ATI in which the iterative algorithm is run.	an admission control on the acceptable arrival rates.		

Table 20. Implementation requirements of individual proposed procedures and mechanisms

Technical contribution	Complexity of the optimization procedures	Complexity at the MBS	Complexity at the FAP	Complexity at the UE	Complexity at network management level
Routing **(CTU)**	• Low complexity, only simple evaluation which routing path (direct or via FAP) is more appropriate	• No specific requirements at the MBS, the procedure is designed only within FAP's range for its users	• Calculation of routing path according to RRC metric, knowledge of proposed MAC messages • FAP has to coordinate all transmission also if direct path is selected	• Knowledge of proposed MAC messages	• As the procedure is implemented only at the FAPs and affects its own users, no complexity is imposed at network level
Fast power control **(CTU)**	• Low complexity, only FAP has to be able to process several simple conditions	• No specific requirements at the MBS, the procedure is designed to adapt transmitting power of FAPs	• Several conditions has to be evaluated in every power adaptation cycle Δt	• No specific requirements at the UE, the UE only has to report CQI as in conventional way	• As the procedure is implemented only at the FAPs, no complexity is imposed at network level
MBMS **(Telkom)**	• Medium complexity, the FAP and MBS should be managed in order to avoid high interference in the MBMS user and support on MBMS transmission support on	• The MBS should support coordination with FAP and support at least one transmission mode, e.g. PtP, PtM and SFN	• The FAP should support coordination with FAP and support multiple transmission mode, e.g. PtP, PtM and SFN	• No specific requirements at the UE, the scheduling is done only according to FAP's backhaul quality	• Medium complexity, as the Core Network elements (eMultimedia Broadcast Multicast Service Center) should coordinate all base stations (MBS and FAP), while in FAP networks specific network element

	both MBS and FAP				(i.e. Femtocell Gateway) coordinates all of FAPs.
Identification **(CTU)**	• No complexity	• Provide number of FAP clusters in the macrocell • If necessary, to evaluate list of neighboring FAPs to deduce the target FAP (in case of handover)	• Requesting PCI (s) of neighboring FAP(s) and to process this information	• When sending the PCI of target FAP, a UE shall provide a list of PCIs of neighboring FAPs (if existing)	• Provide number of FAP clusters in the macrocell
Visiting UE **(CTU)**	• Low complexity, only exchange of few management messages	• Only forwarding messages from V-UE to the target CSG FAP	• For in-band entry, only evaluation of V-UE request. For out-of-band, no changes needed.	• All involved UEs must be able to initiated the procedure for V-UE entry to the CSG FAP • An out-of-band radio (e.g., Bluetooth) is required for out-of-band entry.	• Only exchange of four new management messages must be ensured
Authorization **(CTU)**	• Low complexity, new procedure uses present messages of two procedures.	• No modifications, only FAP and UE are involved in message exchange	• Processing of transferred messages between the UE and the network management level.	• All UEs shall be able to perform new procedure based on already known messages.	• Processing of new procedure: change of allowed CSG IDs based on emergency call initiation, transfer already known messages.
Algorithms based on the exchange of interference pricing **(UPC)**	• High: as in the iterative waterfilling, an SVD decomposition has to be done for the precoder design of each PRB at the transmitting MBS/FAP	Collecting cross-channels and interference sensitivity from MUEs to compute costs values and forward them to interfering FAPs.	• Collecting cross-channels and interference sensitivity from FUEs to compute costs values and forward them to interfering	• Calculation of the interference sensitivity • Measurement of the channel in the link with	• Distribution of information (reference signals) to allow the UEs the measurement of cross-channels from specific

	(direct channel has to be reported even if pricing is not used).		FAPs. • Computing the pricing matrix for the precoder design.	each dominant interferer.	neighbors.
LTE-A adapted pricing mechanisms for MCS and bandwidth part selection **(UPC)**	• Low: Simple decision based on the differences between reported MCS and received pricing information for each bandwidth part and possible beamformer. This decision is taken by the transmitting FAP (MCS has to be reported even if pricing is not used).	• Collecting costs values from MUEs and forwarding this information to interfering FAPs.	• Collecting costs values from FUEs and forwarding this information to interfering FAPs. • Comparing the pricing information received with the reported MCS to select bandwidth part and beamformer.	• Calculation of the interference sensitivity. • Measurement of the individual interference from each dominant interferer for each one of the possible beamformers the dominant interferer can use. • Computation of the MCS degradation due to the transmission from each one dominant interferer for each one of the possible beamformers the dominant interferer can use.	• Distribution of information (reference signals) to allow the UEs the measurement of cross-channels and interference from specific neighbors.
Timer based interference mitigation **(CEA)**	• No complexity	• Medium: monitoring of MBS attached terminals. Generate command to interfering FAPs	• Low: modify scheduling in order to respect forbidding commands received from MBS	• No specific requirements at the UE	• No specific requirements at network management
Backhaul aware	• Medium complexity –	• No complexity	• The adaptive admission	• No specific	• No specific

scheduling **(Telkom)**	the FAP have to do some additional function such as passive monitoring and adaptive admission control.		control have to be aware of the backhaul condition (e.g. bottleneck)	requirements at the UE	requirements at network management
Cross layer optimization **(UDSRLS)**	• Low complexity, only simple iterative algorithm with a very short convergence time is implemented	• No complexity, the MBS are not involved in the procedure	• Knowledge of proposed MAC messages	• Each FUE has to estimate the SINR and fed back to its FAP.	• The proposed algorithms has no impact at the network management level

Table 21. Complexity of individual proposed procedures and mechanisms

8 CONCLUSION

The major goal of the deliverable is to address key aspects regarding femtocell's implementation. The document is primarily focused on control procedures such as routing, power control, multimedia broadcast multicast service, scheduling, identification and authorization procedure. In addition, control procedures to support algorithms developed in WP3 and cross layer optimization issues are tackled.

Novel routing scheme of data transmission for UEs attached to the same FAP has been proposed. The performance of the proposal has been analyzed both analytically and by means of performed simulations. The following concluding remarks can be derived from the evaluations. The throughput achieved by our proposal is always higher than throughput delivered by the conventional scheme. A throughput gain is influenced especially by the ratio of indoor/outdoor traffic and by the FAP's location within the house. The higher amount of indoor traffic leads to the higher throughput gain. The FAP located closer to the middle of the house achieves lower throughput than the FAP located at the edge of the house. Packet delays experienced by UEs in UL are significantly lower for our proposal than packet delays generated by the conventional routing scheme. If the proposal is implemented, UL packet delays are negatively influenced only by the FAP's position. Finally, the performance of the proposal is less degraded for higher PER than the performance of the conventional scheme. Regarding the implementation aspects, the proposal could be easily implemented and does not require any major modifications to standard.

Advanced power control mechanism has been developed within this activity. The algorithm dynamically adapts the transmitting power of FAP depending on the current traffic load and signal quality received at the side of UEs. It has been demonstrated that the results achieved by our power control method are always better as long as the generated traffic is at light or medium levels and sufficient amount of radio resources is allocated to the FAP. Nonetheless, if the size of adaption interval is optimized, proposal performs better at all traffic loads if sufficient amount of radio resources is allocated to the FAP while it still enables the coverage of all users in the house. The benefit of the proposed power control could be seen also in reducing of FAP's power consumption. The problem of existing power adaptation algorithm could be seen in increase of the number of mobility events with extension of adaptation interval length. This issue is addressed by further optimization of the algorithm as we select appropriate target frame utilization. The results show that the proposed adaptation algorithm outperforms the existing one for longer adaptation periods and thus signalling overhead could be reduced. In order to implement the mechanism no modifications to the standard are necessary. In addition, the complexity of proposed power control is low and only simple enhancements have to be done at the side of the FAP.

The MBMS has been evaluated for networks with implemented femtocells. The simulation implemented for both femtocell MBMS and MBS MBMS are evaluated and analysed. The results show the comparison of three MBMS bearer transmission technique, i.e., PtP, PtM and SFN. Based on the result it can be concluded that SFN shows best performance compared to the other two techniques. Not only in the femtocell's based MBMS but also in MBMS without femtocells. This can be achieved for SFN because the timing synchronization and shared resources used in this mode can efficiently transmit the data to all users. In addition, results also show that femtocell implementation of MBMS outperforms the implementation of MBMS in MBS in order to serve femtocell service area with multimedia services. This can be a promising start to other deep and vast research on the implementation of MBMS in femtocell network.

A novel structuring of the cell identifier (PCI) has been proposed. The proposal extends the PCI structure with new identifier that can be either implemented as an extension or as sub-identifier of the currently used PCI format. The advantage of the propose structure is that makes possible to dynamically adjust the range of used PCIs according to the femtocell density of a given macrocell, i.e., the range of PCI can be updated in time and it is independent from macrocell to macrocell. As to the PCI selection itself, by considering a large number of FAPs and not knowing positions of all FAPs in a macrocell, a decentralized method using radio environment scanning combined with a central network entity storing available FAP positions seems to be the most appropriate approach.

An access to a CSG FAP by the UE with no right to access this FAP (i.e., the UE is not in the CSG FAP whitelist) can lead to a complication in emergency situation especially if the CSG FAP interfere too much to the UE and this UE is not able to access its former serving cell. Therefore, the procedure how to inform even the CSG FAP and accept the emergency call is proposed in this document. Moreover, we proposed scheme when a visiting UE can access the CSG FAP even in non-emergency situation. In this case, the access must be agreed and confirmed by the CSG FAP subscriber. This way, the subscriber can temporarily grant an access of a visiting UE to its own FAP. The proposed algorithm makes the overall procedure simpler from the user point of view. Thus this procedure can be performed even by less experienced users.

To support the measurements and information exchange required by the coordination algorithms developed in WP3, control procedures have been specified and new information elements have been defined. For the precoder design, additional requirements due to the coordination are the measurement and reporting of the interference sensitivity and the cross-channels with dominant interferers by the UEs and the forwarding of cost values by FAPs/MBS that will be used to calculate the pricing matrix. The requirements are similar for the coordinated bandwidth and beamformer selection algorithm designed specifically for LTE-A. In this algorithm, however, the reporting and information exchange has to be done per bandwidth part (and beamformer) instead of per PRB. In both cases, the degradation due to the quantization of the information exchanged between FAPs (and MBS) has been evaluated. For the feedback of the unitary cross-channel vectors the codebooks already defined in LTE-A have been considered, and the additional scalar quantities have been quantized with a limited number of bits. Quantization implies some loss with respect to perfect information exchange. However, even if a low number of bits per cost value is employed, this degradation is low enough to consider valid the conclusions obtained in D3.2.

Timer based interference mitigation has been shown to significantly reduce downlink femtocell to macrocell interference, when both tiers share the same spectrum, and when closed mode is assumed for femtocell access. Evaluation has been carried out together with opportunistic scheduling, in order to check that such improvement is not achieved at the expense of opportunistic scheduling efficiency.

The BAS has been simulated and evaluated in order to measure the performance of FAP, either using BAS or not using BAS. The simulation results shows that the FAP utilizing BAS can achieve better performance compared to the non BAS one.

Optimal scheduling strategy based on *cross-layer* optimization has been proposed. A cross-layer optimization requires that the power allocation among the users in each cell can be chosen according to some *throughput optimal* scheduling strategy. Because of the FAPvsFAP interference the optimal scheduling strategy in each cell depends on the power allocations used by the other FAPs. Hence, to compute the globally optimal power allocation for all the FAPs, a centralized control that solves this problem is required. Since the FAPs are not co-located, a centralized solution that requires exchange of signaling among the cells cannot, in general, be implemented. Thus, we focused on *non cooperative* solutions based on distributed algorithms that do not require any coordination among different FAPs. Such a solution is suitable when the backhaul link is not available or its quality is not good enough to guarantee a reliable exchange of information. We formulated the system design within the GT framework. After investigating the conditions for the existence and uniqueness of NE we found a simple iterative scheme (which takes the form of a waterfilling-like solution) to reach that NE. Finally, we assessed through numerical simulation the performance of the proposed scheme. Interestingly we showed that it is always possible to find a stability region, i.e., a set of packet arrival rates for which the total queue size maintains finite.