ICT-248891 STP FREEDOM

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

D2.1

Scenario, requirements and first business model analysis

Abstract:
This deliverable is the first of FREEDOM project. It provides an outlook of the scenarios and assumptions widely shared in the wireless community when addressing femtocell deployment. It starts by providing scenarios as seen from the business perspective, and then they are further described with a more technical perspective. Both interference and mobility are addressed although from the review of foras and standardization bodies, the interference issues are more extensively considered. From these scenarios we derived a list of requirement that should be met by femto-cell systems. These requirements must drive the technical work in the other work-pacakges of FREEDOM. The report then captures the main assumptions for simulation in order to align the work from various WPs and partners around similar set of assumptions. A final section presents true business model from operator standpoint, highlighting the potential of massive femto-cell deployment.

Keyword list: femto-cell, IMT.ADV, LTE, 802.16m, scenarios, requirements
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Executive Summary

The success and the impact of a collaborative project such as FREEDOM is based on the ability of the project consortium to address together relevant problems which are anticipated by the industry. Femto-cells are foreseen to become a key enabler of capacity and coverage improvement for next generation cellular systems (IMT.ADV) and could become in addition the bridge between in-home entertainment systems and mobile communication systems. However, a massive deployment of femto-cells raises numerous technical problems which need indepth analysis. The basic requirements and assumptions for this analysis are described in this document.

This deliverable aims at providing a clear list of scenarios, requirements and assumptions that could be shared by the partners during the whole duration of the project. These scenarios and assumptions are derived from two main sources. The first source is from operator business scenarios and models; the second source is obviously the already huge contributions from standardisation bodies and for a related to femto-cells. One can mention the 3GPP, the IEEE, the Femto Forum and even the ITU.

Indeed, the first section of the deliverable starts from a survey originated by the ITU to understand the level of maturity of the activity of the industry related to femto cells. From the answer to this survey, we simply propose a set of definition to get a common terminology throughout the project.

Section 2 presents high level scenarios as they can be seen from an operator standpoint. This section takes into account the feedback the project received from the Advisory boards made of representant of various operators. Two main scenarios emerge: use of femto-cell for in-home coverage and use of femto-cells for small business areas coverage (e.g. corporate usage). Both cases raises similar issues such as mobility and interference management between the femto and the macro layers. However, from a business perspective, it is foreseen that the corporate case is more likely to happen first. As a result, it is expected that FREEDOM will focus on the corporate case as its primary scenarios. The section 2 pursues in providing scenarios and uses cases from analyzing contributions done in 3GPP and in WiMAX context (both WiMAX forum and IEEE 802.16). It should be noted that from these various bodies, the scenarios are very similar.

Following this high level description of scenarios, section 3 provides a more in-depth description of scenarios with additional details on assumptions covering deployment, architecture, mobility, spectrum issues access methods (open access, close group, hybrid access), backhauling options, and to some extend services and management.

Then Section 4 summarizes these scenarios in terms of technical requirements, grouped by topics. It is expected that the FREEDOM project will try to provide innovative solutions to fulfill these requirements.

Section 5 completes the picture by providing general assumptions to be used when doing system simulations. As interference and mobility are two key issues to be addressed, the assumptions provide channel models, interference models (both are actually more details in the Annex), mobility models, traffic and backhaul models, short overview on PHY layer abstraction to be used for system level simulation.

Finally Section 6 presents a business model and value chain related to femto-cell. This first outlook of business model will be completed at the end of the project in WP5 by introducing the impact of the innovation proposed by the project.
DISCLAIMER

The work associated with this report has been carried out in accordance with the highest technical standards and the FREEDOM partners have endeavoured to achieve the degree of accuracy and reliability appropriate to the work in question. However since the partners have no control over the use to which the information contained within the report is to be put by any other party, any other such party shall be deemed to have satisfied itself as to the suitability and reliability of the information in relation to any particular use, purpose or application.

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### List of abbreviations & symbols

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<tr>
<td>3GPP</td>
<td>3rd Partnership Project</td>
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<tr>
<td>AF</td>
<td>Amplify and Forward</td>
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<td>ARPU</td>
<td>Average Revenue Per User</td>
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<td>ARQ</td>
<td>Automatic Repeat reQuest</td>
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<td>ASN-GW</td>
<td>Access Service Network Gateway</td>
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<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
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<tr>
<td>BCH</td>
<td>Broadcast Channel</td>
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<tr>
<td>BER</td>
<td>Bit Error Rate</td>
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<tr>
<td>BLER</td>
<td>Block Error Rate</td>
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<tr>
<td>BSC</td>
<td>Base Station Controller</td>
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<tr>
<td>BTS</td>
<td>Base Transceiver Station</td>
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<tr>
<td>BW</td>
<td>Bandwidth</td>
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<tr>
<td>CDF</td>
<td>Cumulative Density Function</td>
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<td>CDMA</td>
<td>Code Division Multiple Access</td>
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<tr>
<td>CF</td>
<td>Carrier Frequency</td>
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<tr>
<td>CFO</td>
<td>Carrier Frequency Offset</td>
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<tr>
<td>CN</td>
<td>Core Network</td>
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<tr>
<td>CPE</td>
<td>Customer Premises Equipment</td>
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<tr>
<td>CR</td>
<td>Cognitive Radio</td>
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<tr>
<td>CS</td>
<td>Circuit Switched</td>
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<td>CSG</td>
<td>Closed Subscriber Group</td>
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<td>DL</td>
<td>Down Link</td>
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<tr>
<td>DM</td>
<td>Direct Movement</td>
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<tr>
<td>EESM</td>
<td>Exponential Effective SINR Mapping</td>
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<tr>
<td>EPC</td>
<td>Evolved Packet Core</td>
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<tr>
<td>EPON</td>
<td>IEEE Ethernet standard for PON</td>
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<tr>
<td>ESM</td>
<td>Effective SINR Mapping</td>
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<tr>
<td>e-UTRAN</td>
<td>Evolved UMTS Terrestrial Radio Access Network</td>
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<tr>
<td>FAP</td>
<td>Femto Access Point</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>FFS</td>
<td>For Further Study</td>
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<tr>
<td>FMC</td>
<td>Fixed-Mobile Convergence</td>
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<td>FMS</td>
<td>Fixed-Mobile Substitution</td>
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<td>FTTX</td>
<td>Fiber to the X</td>
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<td>FUE</td>
<td>Femtocell User Equipment</td>
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<td>FWA</td>
<td>Fixed Wireless Access</td>
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<tr>
<td>GEPON</td>
<td>Gigabit Ethernet PON</td>
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<td>GPON</td>
<td>Gigabit PON</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<td>GSM</td>
<td>Global System for Mobile Communication</td>
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<tr>
<td>HARQ</td>
<td>Hybrid ARQ</td>
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<tr>
<td>HC</td>
<td>Header Compression</td>
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<tr>
<td>HCS</td>
<td>Hierarchical Cell Structure</td>
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<tr>
<td>HeNB</td>
<td>Home Evolved Node B (LTE)</td>
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<td>HM</td>
<td>Hysteresis Margin</td>
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<tr>
<td>HNB</td>
<td>Home Node B (UMTS)</td>
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<td>HO</td>
<td>Hand Over</td>
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<tr>
<td>IBI</td>
<td>Inter-Block Interference</td>
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<tr>
<td>IMS</td>
<td>IP Multimedia Subsystem</td>
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<tr>
<td>IP</td>
<td>Internet Protocol</td>
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<tr>
<td>ISD</td>
<td>Inter-Site Distance</td>
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<td>ITU</td>
<td>International Telecommunication Union</td>
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LOS                Line Of Sight
LTE                Long Term Evolution
MAC                Medium Access Control
MCL                Minimum Coupling Loss
MIMO               Multiple-Input Multiple-Output
MISO               Multiple-Input Single-Output
MME                Mobility Management Entity
MMIB               Mean Mutual Information per Bit
MMM                Manhattan Mobility Model
MMS                Multimedia Messaging Service
MOU                Minutes of Usage
MUJE               Macrocell User Equipment
NLOS               Non-Line Of Sight
NSP                Network Service Provider
NUTS               Nomenclature of Unity Territorial Statistic
OFDM               Orthogonal Frequency Division Multiplexing
OFDMA              Orthogonal Frequency Division Multiple Access
PABX               Private Automatic Branch Exchange
PDF                Probability Density Function
PER                Packet Error Rate
PHY                Physical Layer
PON                Passive Optical Network
POP                Point of Presence
PPP                Poison Point Process
PRWMM              Probabilistic Random Walk (Waypoint) Mobility Model
PS                 Packet Switched
QoS                Quality of Service
RAN                Radio Access Network
RAT                Radio Access Technology
RB                 Resource Block
RBIR               Received Bit Information Rate
RBs                Resource Blocks
RF                 Radio Frequency
RLC                Radio Link Control
RN                 Relay Node
RNC                Radio Network Controller
RRC                Radio Resource Control
RS                 Relay Station
RSSI               Received Signal Strength Indicator
SCH                Synchronization Channel
SDO                Standard Development Organization
SIM                Subscriber Identity Module
SIMO               Single Input Multiple Output
SINR               Signal to Interface plus Noise Ratio
SIP                Session Initiation Protocol
SON                Self-Organizing Network
SISO               Single-Input Single-Output
SLG                Service Level Guarantee
SMS                Short Message Service
SNR                Signal to Noise Ratio
TDD                Time Division Duplex
TSG                Technical Specific Group
TTR  Time-division Transmit and Receive
UE   User Equipment
UL   Up Link
UMA  Unlicensed Mobile Access
UMTS Universal Mobile Telecommunication System
VoIP Voice over IP
VSAT Very Small Aperture Terminal
WiFi Wireless Fidelity
WiMax Worldwide Interoperability for Microwave Access
xDSL Digital Subscriber Line
1 SYSTEM DEFINITIONS

This section aims at providing a common set of terminology in the project, which must be followed by all partners. In order to define such terminology, a quick overview on standard and forums has been done.

1.1 Definition from the ITU

Actually, the ITU-R Working Party 5D has made a request for information on Femtocells. Six specific questions were asked by the ITU to get an insight of femtocell standardization status. It should be noted that there is no specific definition of macro-cell, micro, pico nor femtocell. As a result, this initiative from ITU to try to harmonize – or at least – to understand the various definitions of femtocells may not reach to an official standard definition.

The questions were the following:

1) What is your organization’s definition of a femtocell (or equivalent)?
   a) Please provide a general description.
   b) What types of femtocells (or equivalent) are currently being defined by your organization?
2) Standards and specifications
   a) What standards and/or specifications are your group currently involved in that pertains directly to femtocells (or equivalent)?
   b) What is the status and timeline for finalization of these specifications and/or standards?
3) Describe the network architectures being considered.
4) What applications for femtocells (or equivalent) are being considered?
5) What deployment issues are being discussed – for example:
   a) Security
   b) Handover
   c) Reconfiguration
   d) Discovery and association
   e) Frequency bands and power levels
6) How are interference issues being addressed?

Several organizations have replied to this questionnaire. For instance, the Femto Forum (www.femtoforum.org), Broadband Forum (www.broadband-forum.org) and the NGMN Alliance (www.ngmn.org) have cosigned a common answer. The 3GPP has generated an answer too, cosigned by almost all vendors of 3G equipment; the WiMAX Forum and the UMTS Forum have also replied as well as some regional regulation offices.

The sections below summarize the main point of these answers. For details about these answers, please refer directly to the ITU documents [ITUWP5D].

1.1.1 What is your organization’s definition of a femtocell (or equivalent)?

A femtocell is a small, low cost, low power access point, enabling to access to a network operated wireless network, located in user or private premises. The femtocell is connected to the operator’s network through an IP broadband backhaul connection such as fiber, DSL or cable.
This definition is more or less shared by the various respondents. The femto is thus controlled by the operator but installed in private area. As a result, features like self-organization, remote management and possibility for being installed by the user directly are key enablers.

It should be noted that some operators (e.g. NTT Docomo) does not accept direct user’s installation of Femtocell but support the installation and requires a minimum quality for the IP broadband connection to allow the femtocell installation.

Although not specifically stated in the definition, the respondents think that the Femtocells are a solution to increase the capacity and indoor coverage of mobile operator’s networks.

1.1.2 Standards and specifications

The answers to this question basically mention that each organisations (Femto Forum, 3GPP, WiMAX Forum etc.) investigate the topic of femtocell and that the development of the related specifications reaches various level of completion. For instance the 3GPP has released a complete specification for UMTS based femtocells and products exist on the market. The LTE (Release 8) femto solution is frozen (the femtocell is named as the Home NodeB). The LTE (Release 9) and LTE.Advance femto solutions are not yet fully stabilized.

1.1.3 Describe the network architectures being considered.

For the UMTS femtocells, 3GPP has defined an architecture based on the Home NodeB (HNB), a new node called HNB-Gateway that includes some of the functions of the RNC plus specific functions needed by the UMTS femtocells, such as concentration configuration, and security function. The HNB-Gateway is connected through the standard Iu-CS and Iu-PS interfaces to the normal core network of the operators.

For the LTE femtocells, 3GPP has defined an optional concentrator to connect the HeNB to the core network when it is not able to support a very large number of HeNB; the configuration and security functions will have to be hosted by one of the nodes present in the network, possibly by the concentrator. WiMAX Forum has not determined the architectural approach but favours a ‘flat’ IP-based approach.

All groups have defined various models of use: Open access, Close access or Hybrid access. In Open access, all users can get access to the network through the femtocell. In Closed access only the users attached to the femtocell (e.g. the inhabitants of the home) can get access to the network through the femtocell. In Hybrid access, priority is given to owner of the femtocell but additional users can be tolerated. The names of these models and the exact definition of these models differ from one respondent to the other, but the overall principles are similar.

1.1.4 What applications for femtocells (or equivalent) are being considered?

No specific service is defined by the respondents. All mention the benefit of femtocells to offload the macro layer of the mobile network, and to improve indoor coverage.

1.1.5 What deployment issues are being discussed

Again, no specific issue is described and addressed by the respondents. They all mention issues related to link budget, neighbour discovery, synchronisation and interference (femto/femto, macro/femto), mobility, security, integration of femtocell layer with macrocell layer, QoS management, overall management in case of dense deployment, reconfiguration, etc.

These issues are therefore shared by all stakeholders interested in femtocell deployment and indeed, enforce the need to address them in a project such as Freedom.

1.1.6 How are interference issues being addressed?

This question was made specific by the ITU to put the emphasis on one of the key issue related to dense deployment of femtocells. Intensive investigation has already been done, providing to report freely available (e.g. the one from femto-forum http://www.femtoforum.org/femto/Files/File/FF_UMTS-Interference_Management.pdf). However, as stated inside the WiMAX forum answer, “This issue continues to be addressed within the WiMAX Forum with the ultimate objective of self management of interference within the WiMAX network”
Obviously, using a separate spectrum for the femtocell layer is an easy solution, but not all operators will be able to afford to have multiple carriers available for such deployment. As a result, there is still a lot of work to do to mitigate interference when an in-band deployments is used for femtocells.

### 1.2 Summary of definitions

Based on this quick outlook, as well as on the most common definition as used in Femto Forum, 3GPP or WiMAX, the Table 1 summarizes the main definitions and list the one that are used in the FREEDOM project.

<table>
<thead>
<tr>
<th>Description</th>
<th>Femto Forum</th>
<th>3GPP/LTE-A</th>
<th>802.16/WiMAX</th>
<th>FREEDOM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base Station of the macrocell</strong></td>
<td>Macro Node B (MNB)</td>
<td>Macro Node B (MNB)</td>
<td>Macro Advanced BS (Macro ABS)</td>
<td>Macro BS (MBS or BS)</td>
</tr>
<tr>
<td><strong>User attached to the macrocell</strong></td>
<td>Macro User Equipment (MUE)</td>
<td>Macro User Equipment (MUE)</td>
<td>Advanced (AMS)</td>
<td>Macro User Equipment (MUE)</td>
</tr>
<tr>
<td><strong>Femtocell</strong></td>
<td>Femto Acces Point or Home Node B</td>
<td>Home Node B (HNB)</td>
<td>Femto ABS</td>
<td>FAP</td>
</tr>
<tr>
<td>(HNB or FAP)</td>
<td></td>
<td>H(e)NB includes HeNB and FAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Access Station, can be either</strong> FAP or BS</td>
<td></td>
<td></td>
<td></td>
<td>AS</td>
</tr>
<tr>
<td><strong>User attached to the femtocell</strong></td>
<td>Femto UE or Home UE (HUE or FUE)</td>
<td>Home User Equipment (HUE)</td>
<td>AMS</td>
<td>Femto UE (FUE)</td>
</tr>
<tr>
<td><strong>Network element that terminates TR-069 with the femtocell to handle the</strong></td>
<td>Auto-configuration Server (ACS)</td>
<td>Home NodeB Management System (HMS)</td>
<td>Femtocell Management system in Femto Network Service Provider (Femto – NSP)</td>
<td>Femtocell Management system (FAP-MS)</td>
</tr>
<tr>
<td>remote management of a large number of femtocells**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Network element that directly terminates the Iu interface with the</strong></td>
<td>FAP Gateway (FAP-GW)</td>
<td>Home Node B gateway (FAP-GW)</td>
<td>Femto Access Service Network Gateway (Femto-ASN GW)</td>
<td>Femto gateway FAP gateway (FAP-GW)</td>
</tr>
<tr>
<td>femtocell and the existing IuCS and IuPS interface with the core networks**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Handovers femto-femto, BS-femto</strong></td>
<td>Handover (or handoff)</td>
<td>femto-macro: handout</td>
<td>Handover (or handoff)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>macro-femto: hand-in</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Summary of terminology used in standards and within FREEDOM.
2 SCENARIOS

This section describes the scenarios as nowadays envisaged with respect to Femto cells. Those scenarios are thus seen from an operator business standpoint and then derived in a more technical perspective.

Definitely, the various bodies such as Femto Forum, 3GPP, WiMAX Forum etc. already dedicated a lot of effort in defining scenarios and use cases – which are by the way quite similar within these bodies. Therefore, this section provides as well an overview of the scenarios as defined in these bodies:

- The description of the 3GPP and Femto Forum scenarios in sections 2.2 and 2.3 respectively mainly focus on interference scenarios, as interference issue was identified by the various bodies as a key technical concern for enabling mass deployment of FAPs.
- The “use cases” presented in sections 2.4 and 2.5 aim at giving an insight to the requirements and services associated with the dynamic behaviour and the use of the FAPs in the scenarios, as defined in 3GPP-LTE-A (from [3GPP-TS22.220]) and WiMAX (from [ARI09]) respectively.

2.1.1 Business model scenario BM1: Corporate Customer, in Urban/Dense Urban

In this scenario, the femtocell serves an Corporate customer in a dense urban/urban area, in order to provide good coverage in an indoor area.

2.1.1.1 Objective and high level network topology

This scenario has the three following objectives:

- Provide coverage for indoor (more than two floors to high rise building).
- Overcome macrocell capacity issue in urban/dense urban area.
- Enhance Quality of Experience for indoor users in dense urban/urban area especially for corporate users.

The related network topology is characterized by:

- Macrocells are available, but are not able to provide enough indoors coverage and capacity for corporate users.
- Backhaul availability: corporate intranet, metro-ethernet, FTTX (GPON/GEPON), xDSL.
- FAP deployments: from one to many FAPs.
- UE population: medium to high FAP users, medium to high Macro users in the corporate building.
- FAP operator:
  - The FAPs belong to a single cellular operator (A) and only serve its customers.
  - FAPs belong to several operators (A, B or C). Each FAPs group (for example, user group from operator A) may serve users belonging to another operator (for example, B) when there is a roaming agreement (between operators A and B).

2.1.1.2 End User Perspective

Generally the indoor signal level in dense urban/urban area is low since the signal from a macrocell has a low penetration inside buildings (especially in band > 2 GHz). This will limit the maximum throughput experienced by a single user; in addition, during busy hours (daylight) there is a high number of users accessing the macrocell and the aggregate bandwidth per macrocell may be fully shared by users in that areas. As a result, the maximum throughput per user will be reduced as the number of active users increases.

The use of FAPs in enterprise buildings will improve coverage and Quality of Experience in terms of coverage and capacity.

The UE may access services from a cellular operator as well as local IP services (e.g., IP-PABX services, corporate intranet and at the same time through FAP, as described in some use cases in
ICT-248891 STP
Document number: D2.1
Title of Deliverable: Scenario, requirements and first business model analysis

[3GPP-TS22.220]: Usecase-12: FAP interacts with IP-PABX, Usecase-14: Local IP Access) (see section 2.4)

2.1.1.3 Cellular Operator Perspective

A cellular operator experiences difficulty in reaching indoor users due to the nature of obstacles in dense urban/urban area. The deployment of indoor BSs in every building is not always possible because of CAPEX issues, backhaul and space availability. Sometimes, a tenant (building management) has already established exclusive agreement with a single cellular operator and refuses to give space to other operators.

The use of femtocells brings a new approach, allowing an operator the choice to deal with Building Management or Corporate Customer or even end users. Operators may implement FAP Hosting Party policies when they want to deal with Building Management and Corporate Customer in revenue sharing schemes. As an alternative, an operator may directly deal with end users who want FAP available in their office rooms.

The operator may consider an offer over multiple services related to corporate customers needs. The operator may provide a total solution allowing intranet, IP PABX as well as office-based services to be accessed while the users are in the office (served by FAP) and going mobile and served by macrocell.

![Image](AWE Communications)

Figure 1. Network configuration for the business case of corporate customer for a dense urban / urban scenario. (Source: TELKOM Indonesia)

2.1.2 Business model scenario BM2: Corporate Customer, in Remote Area, No 4G Macrocell available

2.1.2.1 Objective and high level network topology

This scenario has the three following objectives:

- Provide 3G/4G coverage for corporate users in remote areas (rural, oil company, offshore, mining etc) assuming the existing backhaul is available.
- Provide 3G/4G coverage for corporate users in area where there is no 4G macrocell.
• Provide mobile application/services for corporate users in remote areas.

The related network topology is characterized by:
• 3G/4G Macrocell are not available.
• Backhaul availability: existing corporate intranet with backhaul types including, VSAT IP and Radio IP Microwave.
• FAP Deployments: from one to many FAPs.
• UE Population: low-to-medium FAP users, no Macro users.
• The FAPs belong to a single cellular operator (A) and may serve other users from other operators (at least one operator, let say B) given that there is a roaming agreement between A and B.

2.1.2.2 **End User Perspective**

Generally, corporate users in a remote area/emerging area are not able to enjoy mobile services because there is no macrocell coverage. They are able to access data services through corporate data access from their office to the rest of world. The backhaul connections usually available are VSAT or Radio IP (WiMAX, microwave, etc.).

FAPs will give 3G/4G coverage allowing corporate employees to use their UE enjoying basic services such as Voice, SMS/MMS, Instant Messaging, Video Conference and other mobile office-based applications.

The users may use the same UE to access local IP services simultaneously through FAP (e.g. IP-PABX services, corporate intranet as described in some usecases in [3GPP-TS22.220]: Usecase-12: HNB interacts with IP-PABX, Usecase-14: Local IP Access, see Section 2.4for details)

2.1.2.3 **Cellular Operator Perspective**

Cellular operator is reluctant to provide macrocell in remote area/emerging city due to backhauling issue (small number of requests). By adopting FAPs, a cellular operator can provide services to scattered corporate users in remote area / emerging city given that the potential customers already have high speed data connectivity (VSAT, Radio IP, etc).

Femtocell brings a new approach, since Operator may choose to deal with Building Management or Corporate Customer or even end users. Operator may implement FAP Hosting Party policies when their want to deal with Building Management and Corporate Customer in revenue sharing schemes. Other alternative, Operator may directly deal with end users who want FAP available in their office rooms.

The operator can offer multiple services related to corporate customers needs. Operator could provide total solution allowing intranet, IP PABX as well as office-based services to be accessed while the users in the office (served by FAP) and going mobile and served by macrocell.
2.1.3 Business model scenario BM3: Residential Customer, in Urban/Sub-urban

2.1.3.1 Objective
This scenario has the three following objectives:

- Provide coverage for indoor.
- Overcome macrocell capacity issue in urban/sub-urban area.
- Enhance Quality of Experience for residential users in urban/suburban area especially heavy usage data users.

The related network topology is characterized by:

- 3G/4G Macrocell are available.
- Backhaul availability: xDSL, FTTx.
- FAP Deployments: one – two FAP.
- UE Population: low FAP users, low-to-medium Macro users.
- The FAPs belong to a single cellular operators (A) and may serve other users from other operators (at least one operator, let say B) given that there is a roaming agreement between A and B.
- Access method: Closed to Hybrid from same operator.

2.1.3.2 End User Perspective
A residential user with xDSL/FTTx connectivity who has subscribed to a cellular operator. Unfortunately the cellular signals inside the house is weak and connectivity is unstable (call drop or high rate of disconnections). FAP can be installed in the house to overcome the problem, improve the coverage and increase the maximum throughput.
The user is able to access services including:

- Home networking (private IP networking);
- Internet access from xDSL service provider;
- Mobile services from a cellular operator.

Those services can be simultaneously accessed from any UE connected to a FAP.

The UE may freely move in the house, staying connected to a FAP, however he might also move outside, where the macrocell coverage is available and handover occurs during voice conversation or other data transaction.

2.1.3.3 Cellular Operator Perspective

A cellular operator may propose FAP to the user to be used in its home. The Operator registers the location of the femtocell and offer Femtozone Service in the customer’s home.

Calls in Femtozone may be charged on flat-rate basis or even be free. Actually the business model (including the billing scenario) will be elaborated with more details in section 6 and in the next deliverable.

The operator might give either a closed access (CSG) method to the user or hybrid access method. The latter can be used, for instance, in case the residential user has a guest who wants to use the FAP services. If the guest is from a different operator, the service is granted as long as there is roaming agreement between hosted FAP and third party operators.

Figure 3. Network configuration for the business case of residential customer in urban/suburban area. (Source: TELKOM Indonesia)

2.2 Technical scenarios as defined in 3GPP

2.2.1 3GPP Deployment configurations

In [3GPP-TR25.820] the 3GPP, in view of evaluating the impact of the FAP on the macro layer, has devoted particular emphasis to the downlink.
The actual view has emphasized several interference scenarios regarding the relative positions and transmission activities of the possibly interfering players, as reported in Figure 4.

![Interference Scenarios Diagram](image)

**Figure 4. 3GPP basic interference scenarios, from [FEM-INT08]**

The attention under the 3GPP development has been focused on investigating the impact of FAP deployment on the existing BS requirements. To this purpose, since the interference scenarios are dependent on deployment configurations, the study has been considered on the basis of the deployment characteristics related to the possible options for a UE to attach to a FAP or not, in particular:

- **Open access or CSG (Closed Subscriber Group)**
  - Open access FAPs can serve any UE in the same way as the normal BS;
  - CSG FAPs only serve UEs which are members of a particular CSG.

- **Dedicated carrier or co-channel**
  - Depending on FAPs operating in their own or separate channel, or whether they share a carrier with an existing (e)UTRAN network.

Both these aspects become particularly relevant when the core and the mobile networks belong to different operators.

There is still the possibility for an operator to choose how to manage FAP power which can be:

- **Fixed**: FAPs have set a fixed maximum transmit power
- **Adaptive**: FAPs have the possibility to evaluate interference with the environment and adjust transmit power.

A fixed FAP transmit power in general does not give good performance and, hence FAP transmit power needs to be adapted to provide acceptable performance for FUEs and MUEs (self-calibrated transmit power algorithm for FAPs). FAP transmit power has to be calibrated properly according to the deployment scenario as well as the signal strength of macrocell and/or other FAPs to maintain a reasonable coverage for the FAP and an acceptable coverage for the macro (coverage holes – dead zones). In uplink there is a need of adaptive attenuation (or AGC) at the FAP to achieve good FUE uplink performance and minimize the negative impact on the macro uplink. For example, a significant UL interference can appear in a situation with neighbouring FAPs with CSG (see Figure 5).
The effort to enhance the coverage of UMTS/LTE in the home environment expected by the FAPs deployment strongly affects interference management, especially in the case of CSG access scheme.

For what regards mobility of UEs, the scenarios to be considered must be able to support UE speeds up to 30 km/h.

In the consideration of the possible interference schemes one has to structure the analysis allowing potentially a very high density of 3G FAPs; in the current status such a scheme such is considered in which in each macro cell there is a fixed number of FAPs (50, 100, 200 and 500), placed randomly in each macro cell.

In current evaluations [R4-070902], macro cell terminals can be supposed either outside either inside buildings. The transmit power of each FAP spans from 20 dBm to 24 dBm.

For what regards the penetration loss (power attenuation suffered by the UE), as far as the UE is located outdoors, the one relevant to the link to the femtocell is 10 dB and to the BS is 0 dB. On the other side, when the UE is located indoors, the penetration loss relevant to the UE-FAP link is 0 dB and the one relevant to the BS-UE link is 10 dB.

Performance evaluation with respect to RF requirement analysis by 3GPP is quantified in terms of UE throughput, coverage, and spectral efficiency, taking into account cell edge and average UE.

When considering in details the proposed scenarios, it will be necessary to cope with several possible situations of spectrum assignments, based on the use of licensed spectrum by the license holder (like as an operator), who is in turn responsible to ensure that all emissions comply with associated regulatory requirements. Although if the solution to this problem has not yet been addressed, it is clear that the operator should be able to verify that the FAP is employing its own licensed frequencies (channels) that could in principle depend on the specific geographical region.

The deployment configurations must take into account the following parameters:

- FAP location;
- Communication link between FAP and FAP operator;
- FAP identity.

3GPP introduces specific requirements about FAP location such as a FAP displaced within operator’s license area when transmitting on the radio path. In some specific circumstances, the exact position of the FAP can be required for emergency services, lawful interception or for restricting operation to a specific location.
The communication link between FAP and FAP operator must be active to allow the FAP receiving authorisation and satisfy the minimum performance requirements for the services offered, as requested by the UE operator. In addition, the FAP operator must be able to verify the FAP identity.

The deployment configurations considered so far by the 3GPP are the following:

- Deployment A. CSG, Dedicated channel, Fixed power;
- Deployment B. CSG, Dedicated channel, Adaptive power;
- Deployment C. CSG, Co-channel, Adaptive power;
- Deployment D. Partial Co-channel;
- Deployment E. Open Access, dedicated or co-channel.

The deployment scenarios listed above will be detailed in the subsequent paragraphs.

### 2.2.1.1 Configuration A. CSG, Dedicated channel, Fixed power

In this deployment the FAP is configured as a Closed Subscriber Group and the access to the FAP is managed by the agreement between the FAP owner and the network operator. From a system point of view, the access is allowed to a limited number of UE while the majority of UE in the cell do not have access to the FAP. From the interference point of view, since the FAP is deployed in channels different from the ones employed by the macro network, the worst case is that of the interference associated with adjacent channels licensed to different operators.

A relevant case of interference between different FAPs arises from the co-channel interference within a dense population of FAPs. Although the operator could limit the maximum transmit power of the FAP, limiting the effect of the FAPs over the macro network, this limits the size of the FAP cell (the operator can set different maximum power emission depending on the position in the macrocell, in particular at the edge).

### 2.2.1.2 Configuration B. CSG, Dedicated channel, Adaptive power

In the case of a FAP configured to operate in a dedicated channel, the maximum transmit power can be set to the maximum available, leaving open the possibility to exceed such maximum value only in selected cases, still producing an acceptable level of interference.

### 2.2.1.3 Configuration C. CSG, Co-channel, Adaptive power

The FAP operates in the same channel as the macro network, providing the worst case interference deployment, and the power levels of the FAP and its associated FUE must be tuned for appropriate functioning, excluding the case of maximum transmit power fixed in advance.

### 2.2.1.4 Configuration D. Partial Co-channel

This case of deployment represents a partial overlap between the frequencies used by the FAP and the whole band of the macro layer, as represented in Figure 6. The MUE can operate on any frequency, although those operating in the overlapping part of the spectrum can change to the clear or most favourable part.

This spectrum configuration must be considered also in the Open Access (Deployment E), thus allowing an overall control of the FAP influence on the whole network, also in the case of mobility.
For UTRAN, a hybrid implementation over two channels has been proposed (Figure 7), one for Macro BS+FAP, the other for the Macro BS only, thus MUE can suffer enough FAP interference to induce handover to the other channel.

![Figure 7. Spectrum arrangement for UTRAN, from [3GPP-TR25.820]](image)

Finally, another solution for e-UTRAN has been proposed, due the scalability of the channel width (Figure 8). If the HeNB (Home evolved Node B) sub-band does not overlap with the central 6 RBs (around the DC) of the macro channel, it will allow anyway the UE to receive the broadcast and synchronisation channels connecting to the macro layer and the procedures for the frequency change will be able to switch from one frequency to the other, as needed.

![Figure 8. Spectrum arrangement for e-UTRAN, from [3GPP-TR25.820]](image)

### 2.2.1.5 Configuration E. Open Access dedicated or co-channel

The deployment of a FAP serving any UE with a completely open access is represented similarly to the service offered by any other displacement of several BSs. This scenario is assumed by the 3GPP as the one where only several BSs are present, without specific details about the installation possibilities of the FAP in the macrocell.
2.2.2 3GPP Interference scenarios

The environments to implement interference scenarios envisaged by the 3GPP have been so far classified according to the effect of the presence of FAP over the actually present BSs and deployments of UEs in the cell. The performance of the FAPs will be affected by the other emitters around.

The interference scenarios are summarized in the following Table 2.

<table>
<thead>
<tr>
<th>Scenario number</th>
<th>Aggressor</th>
<th>Victim</th>
<th>Deployment of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>UE attached to FAP</td>
<td>Macro BS Uplink</td>
<td>Any</td>
</tr>
<tr>
<td>2</td>
<td>FAP</td>
<td>Macro BS Downlink</td>
<td>A, B, C, E</td>
</tr>
<tr>
<td>3</td>
<td>UE attached to Macro BS</td>
<td>FAP Uplink</td>
<td>B, C</td>
</tr>
<tr>
<td>4</td>
<td>Macro BS</td>
<td>FAP Downlink</td>
<td>Any</td>
</tr>
<tr>
<td>5</td>
<td>UE attached to FAP</td>
<td>FAP Uplink</td>
<td>A</td>
</tr>
<tr>
<td>6</td>
<td>FAP</td>
<td>FAP Downlink</td>
<td>A, B, C</td>
</tr>
<tr>
<td>7</td>
<td>UE attached to FAP and/or FAP</td>
<td>Other system</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Other system</td>
<td>UE attached to FAP and/or FAP</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>FAP mobile</td>
<td>Serving FAP</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. 3GPP scenarios for interference analysis.

In this view, the proposed schemes constrain the number and type of parameters that can be adapted to adjust the system performance. In particular, for Scenario 1 the transmit power of the UE should be controlled while the other scenarios must be considered jointly with the mentioned Deployment types.

2.2.3 Mobility scenarios

The 3GPP project has considered some cases of mobility for the FAP (Figure 9):

- FAP is out of coverage from any macro cell, either GSM or UMTS;
- FAP under coverage of macro GSM;
- FAP under coverage of macro UMTS, using the same frequencies as the macro;
- FAP under coverage of macro UMTS, using different frequencies from the macro.

The cases 2 and 4 with good macro coverage would not imply for a UE to search for a FAP, while in general the Standard prescribes to prioritize the selection of a FAP, when available.

Cell reselection parameters have already been introduced in order to encourage a UE to select a FAP and stay there once camped. The actual framework prescribes that a UE registered to a macro layer can automatically find FAP cells and, once camped there, the UE prioritizes the femtocell. A drawback of this prescription relies on the continuous attempt of the UE to continue measuring the highest rank cells and trying to register, impacting on battery consumption and adding management signalling load on the CN.
Figure 9. Possible implementation of a FAP mobility scenario

The cell reselection process relies on the implementation of dedicated techniques to track the different cells and on flexibility for the identification and distinction between macrocells and FAPs. The UE can have assigned a set of parameters defining a priority scale for cells in range (one or more macro, or FAP), taking into account and evaluating an appropriate measure for FAP cells also when the UE is still in good macro coverage. Such process relies on at least two reselection rules.

- For the UEs in range of other (macro) cells with an assigned scale of priority, the search for FAP by the UE is limited to reduce the measurement effort.
- The mobility signalling can be mitigated by implementing a hierarchical cell structure (HCS) with penalty timer. The UE will be prevented from choosing a certain cell for the duration of the timer: this is to impose a minimum time in the range of a FAP before performing sensing and HO to it and avoid that a moving UE in proximity of a cell just for a short time select this cell. The UE can be prevented from performing superfluous HO also by purposely defining a set of parameters for a “high mobility” condition regarding the UE. In this way, a UE would be induced to select macrocells instead of searching for a FAP.

2.3 Scenarios as defined in Femto Forum

Femto Forum (in contrast to 3GPP/3GPP2 or WiMAX Forum) is not a SDO (Standard Development Organization) and is devoted to the worldwide promotion of femtocell technology. Femto Forum published documents entitled *Interference Management in UMTS Femtocells*, adapted to frequency band 2GHz [FEM-INT08] and 850-900MHz [FEM-INT10], exploring different simulation scenarios regarding the problem of femtocells radio interference management. They are reassumed below and can serve as a basis for the proposal of the operational scenarios examined by FREEDOM. In these scenarios four different entities are considered: Macro BS, FAP, UE connected to Macro BS or to FAP. The possible interference relations (downlink and uplink) can be classified as:

- Scenario A: Macro BS (downlink) to FUE;
- Scenario B: MUE (uplink) to FAP;
- Scenario C: FAP (downlink) to MUE;
- Scenario D: FAP (uplink) to MUE;
- Scenario E: FAP (downlink) to nearby FUE;
- Scenario F: FUE (uplink) to nearby FAP;
- Scenario G: Macro BS (downlink) to adjacent-channel FUE;
- Scenario H: MUE (uplink) to adjacent-channel FAP;
• Scenario I: FAP (downlink) to adjacent-channel MUE;
• Scenario J: FUE (uplink) to adjacent-channel MUE.

The interference scenarios proposed by Femto Forum are based on the efforts done by 3GPP RAN4 within the study of the radio interface feasibility of FAP (RAN#39) and presented in [3GPP-TR25.820]. The scenarios were foreseen for the W-CDMA air interface technology, frequency band of 900 MHz or 2 GHz and Closed Subscriber Group (CSG). A part of this work included also an anticipated study of FAP interference scenarios deployments. The scenarios examine the management of the radio interferences between the macro and femto layers since this problem is of great importance in femtocell technology development and implementation. The presented scenarios can be defined as “worst-case” and thus indicating limits of femtocell network deployment in terms of radio interferences.

Indeed, to mitigate the interferences a detailed theoretical study was done by Femto Forum in order to indicate and classify the most important scenarios of FAPs deployments. The interference scenarios are detailed in the following subsections.

2.3.1 Scenario A: Macro BS (DL) to FUE (DL) and co-channel deployment

Scenario A (Figure 10): Macrocell downlink interference to the femtocell UE receiver; a femtocell is located on a table next to the apartment window that is in the direct bore sight of a rooftop macrocell (approx. 30m distance); the macrocell is fully loaded, while a UE is connected to the femtocell at the edge of its range; 3GPP analysis references: [R4-071941], [R4-072004], [R4-080149], [R4-080150].

An extended version of this scenario includes femtocells located further away from the macro BS.

![Figure 10. Femto Forum scenario A, from [FEM-INT08]](image)

2.3.2 Scenario B: Macro UE (UL) to FAP (UL) and co-channel deployment

Scenario B (Figure 11): Macrocell uplink interference to the femtocell receiver; a femtocell is located on a table within the apartment; weak coverage of the macro network is obtained throughout the apartment; a user that does not have access to the femtocell (MUE) is located next to the femtocell; another user device (FUE) is connected to the femtocell and has an ongoing call at the edge of femtocell coverage; 3GPP analysis references: [R4-070825], [R4-070969], [R4-070970], [R4-071619], [R4-071941], [R4-072004], [R4-080097], [R4-080409], [R4-080153].
2.3.3 **Scenario C: FAP (DL) to MUE (DL) and co-channel deployment**

Scenario C (Figure 12): Femtocell downlink interference to the macrocell UE receiver; a Macro UE (MUE) is connected to the macro network at the edge of coverage; the MUE is located in the same room as an active femtocell (to which it is not allowed to access); the femtocell is fully loaded in downlink; 3GPP analysis references: [R4-071231], [R4-071253], [R4-071263], [R4-071540], [R4-071554], [R4-071578], [R4-071660], [R4-071661], [R4-072004], [R4-071941], [R4-080409], [R4-080151].

2.3.4 **Scenario D: FUE (UL) to Macro BS (UL) and co-channel deployment**

Scenario D: (Figure 13) Femtocell uplink interference to the MUE receiver; a FUE is located next to the apartment window, that is in the direct bore sight of a rooftop macro BS (approx. 30m distance); at the same time the FUE is connected to the femtocell at the edge of its range, and transmitting at full power; 3GPP analysis references: [R4-070969], [R4-070970], [R4-071231], [R4-071578], [R4-071619], [R4-071941], [R4-072004], [R4-080409], [R4-080154].
2.3.5 Scenario E: FAP (DL) to neighbour FUE (DL) and co-channel deployment

Scenario E (Figure 14): Femtocell downlink interference to nearby femtocell UE receivers; In first case, two apartments are separated by a wall, with a femtocell being deployed within each apartment; the two femtocells being considered are denoted AP1 and AP2; each femtocell supports a corresponding UE – namely, UE1 and UE2 respectively; the assumption is that UE2 is not located in its own apartment, but rather in the apartment where AP1 is operating; Therefore, UE2 is at the edge of coverage of its own femtocell, but very close (<3m) to AP1 (ie. a foreign femtocell);

In second case, two houses are detached with a femtocell being deployed within each house.; the two femtocells being considered are denoted AP1 and AP2; Each femtocell supports a corresponding UE – namely, UE1 and UE2 respectively; the assumption is that UE2 is not located in its own house, but rather in the house where AP1 is operating; Therefore, UE2 is at the edge of coverage of its own femtocell, but very close (<3m) to AP1 (ie. a foreign femtocell);

3GPP analysis references: [R4-071617], [R4-071618], [R4-080409], [R4-080151], [R4-080149], [R4-080150], [R4-081344]
Interference to the home user from the neighbours and the macrocell is analyzed; the simulation layout for this scenario is given in Figure 15.

![Village Plan](image)

Figure 15. Village plan – each house has a femtocell, from [FEM-INT08]

2.3.6 Scenario F: Neighbour FUE (UL) to FAP (UL) and co-channel deployment

Scenario F (Figure 16): Femtocell UE uplink interference to nearby femtocell receivers; two apartments are adjacent to each other; femtocells (AP1 and AP2) are located one within each apartment; the owner of AP2 visits their neighbor’s apartment, and is on the edge of coverage of their own femtocell; the owner of AP2 establishes a call that requires peak UE power to their own femtocell while they are located next to the AP1 (inferior to 3m); 3GPP analysis references: [R4-070971], [R4-071185], [R4-071617], [R4-071618], [R4-080409], [R4-080152], [R4-080153].

![Scenario F Diagram](image)

Figure 16. Femto Forum scenario F, from [FEM-INT08]
2.3.7 Scenario G: Macro BS (DL) to FUE (DL) and adjacent channel deployment

Scenario G (Figure 17): Macrocell downlink interference to the adjacent channel femtocell UE receiver; a femtocell UE is located on a table next to the apartment window and is in the direct bore sight of a rooftop macrocell (approx. 30m distance); the macrocell becomes 50% loaded, while a femtocell UE is connected to the femtocell at the edge of its range; 3GPP analysis references: [R4-071941], [R4-072004], [R4-080409], [R4-080149], [R4-080150].

![Figure 17. Femto Forum scenario G, from [FEM-INT08]](image)

2.3.8 Scenario H: MUE (UL) to FAP (UL) and adjacent channel deployment

Scenario H (Figure 18): Macrocell UE uplink interference to the adjacent channel femtocell receiver; a weak signal is received from the macro BS within the apartment where the femtocell is located; it is assumed that the macro and femto cellular layers are deployed on adjacent frequencies; a MUE is located in close proximity to the femtocell and has a call established at full power; a FUE has an ongoing call at the edge of the femtocell coverage; 3GPP analysis references: [R4-070825], [R4-070971], [R4-071185], [R4-071941], [R4-072004], [R4-080097], [R4-080409].

![Figure 18. Femto Forum scenario H, from [FEM-INT08]](image)
2.3.9 Scenario I: FAP (DL) to MUE (DL) and adjacent channel deployment

Scenario I (Figure 19): Femtocell downlink interference to the adjacent channel macrocell UE receiver; two users (UE1 and UE2) are within an apartment; UE1 (FUE) is connected to a femtocell at the edge of coverage; UE2 (MUE) is connected to the macrocell at the edge of coverage, and located next to the femtocell transmitting at full power; the macro and femto-cellular layers are deployed on adjacent frequencies; 3GPP analysis references: [R4-071211], [R4-071231], [R4-071263], [R4-071540], [R4-0715554], [R4-071660], [R4-071661], [R4-072004], [R4-071941], [R4-072025], [R4-080409], [R4-080151].

![Figure 19. Femto Forum scenario I, from [FEM-INT08]](image1)

2.3.10 Scenario J: FUE (UL) to Macro BS (UL) and adjacent channel deployment

Scenario J (Figure 20): Femtocell UE uplink interference to the adjacent channel macrocell BS receiver; a FUE is located next to the apartment window, in direct bore sight of a rooftop macrocell (approx. 30m distance); FUE is connected to the femtocell at the edge of its range, and is transmitting at full power; 3GPP analysis references: [R4-070971], [R4-071185], [R4-071231], [R4-071619], [R4-071941], [R4-072004], [R4-080409], [R4-080152].

![Figure 20. Femto Forum scenario J, from [FEM-INT08]](image2)

A summary of these scenarios is given in the Table 3.
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Shared spectrum</th>
<th>Aggressor</th>
<th>Victim</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Yes</td>
<td>Macro BS DL Tx</td>
<td>Femto UE DL Rx</td>
</tr>
<tr>
<td>B</td>
<td>Yes</td>
<td>Macro UE UL Tx</td>
<td>Femto AP UL Rx</td>
</tr>
<tr>
<td>C</td>
<td>Yes</td>
<td>Femto AP DL Tx</td>
<td>Macro UE DL Rx</td>
</tr>
<tr>
<td>D</td>
<td>Yes</td>
<td>Femto UE UL Tx</td>
<td>Macro BS UL Rx</td>
</tr>
<tr>
<td>E</td>
<td>Yes</td>
<td>Femto AP DL Tx</td>
<td>Neighbor Femto UE DL Rx</td>
</tr>
<tr>
<td>F</td>
<td>Yes</td>
<td>Neighbor Femto UE UL Tx</td>
<td>Femto AP UL Rx</td>
</tr>
<tr>
<td>G</td>
<td>No</td>
<td>Macro BS DL Tx</td>
<td>Femto UE DL Rx</td>
</tr>
<tr>
<td>H</td>
<td>No</td>
<td>Macro UE UL Tx</td>
<td>Femto AP UL Rx</td>
</tr>
<tr>
<td>I</td>
<td>No</td>
<td>Femto AP DL Tx</td>
<td>Macro UE DL Rx</td>
</tr>
<tr>
<td>J</td>
<td>No</td>
<td>Femto UE UL Tx</td>
<td>Macro BS UL Rx</td>
</tr>
</tbody>
</table>

Table 3. FAP interference scenarios considered by Femto Forum.

Please, note that the difference between scenarios A-to-D and scenarios G-to-J is in the channel deployment (co-channel vs. adjacent channel). The set of scenarios presented above is illustrated graphically in Figure 21.

![Figure 21. Femto Forum’s interference scenarios A to J, from [FEM-INT08]](image)

2.4 Use cases as defined in 3GPP

Below, a set of use cases considered by 3GPP ([3GPP-TS22.220]) is listed:

Use case-1: FAP mobility

User A connects to the FAP via mobile device. User A should be able to move around within the FAP coverage in the home or enterprise. User should also be able to invoke additional services based on user policy and operator policy.

Use case-2: FAP guest users

User A and User B are subscribers of Operator 1 and Operator 2 respectively. User A visits User B in his home and User B allows User A to use FAP in User B’s home. User A should be able to access all
the services he is subscribed to from Operator 1 based on the policies set by User B and operator 2. Operator 1 and Operator 2 have roaming agreement.

Use case-3: FAP – BS handovers

User A subscribes to cellular services of Operator 1 and is authorised to access a FAP from same or other operator. User A starts service in the FAP coverage and continues moving into a cellular network. Similarly User A starts service in cellular network and continues moving into FAP coverage. User A does not see any impact on services due to mobility in both cases.

Use case-4: Access to home based services

User A connects to the FAP via mobile device. User A should be able to access home based services (e.g. local digital media servers and digital media players) from the mobile device. Other users may access the home based services subject to FAP Hosting Party policies.

Use case-5: Media transfer

User A connects to the FAP via mobile device. User A starts viewing video streaming service on the mobile device. User A then wants to continue viewing the video on a different screen for better viewing. User A should be able to transfer the session to a high-definition TV or PC connected via broadband connection. User A should also be able to transfer the session from the TV or PC to a mobile device and continue the session in the FAP coverage and also in the cellular network.

Use case-6: IMS capable FAP used for coverage purposes

In this scenario, the reason for an operator to introduce IMS (IP Multimedia Subsystem) capable FAP is to offload voice traffic from his existing CS (Circuit Switched) core network to IMS. However, as in this scenario the usage of ‘legacy’ services (e.g. CS Fax) is still assumed - only the utilization of network resources is to be changed - it is requested that IMS capable FAP provides all the services/capabilities that are provided through regular BS from the beginning.

Use case-7: IMS capable FAP for a new business model

This scenario starts with a view that FAP is located in the user’s residence and the UE is the preferred equipment to interact with home services/applications. New business can be expected there. In this scenario, some of the CS services/capabilities that are provided through regular BS might not be needed or might be provided in a later step if the operator could instead offer attractive new services under IMS capable FAP only.

Use case-8: IMS capable FAP for Green field operator

This scenario expects new players to get into the mobile market. In this scenario, they would aim to deploy cost efficient and future proof infrastructure, i.e. no CS domain but IMS/PS domain only, regardless of whether or not UEs have IMS client on them.

Use case-9: Hybrid access mode

In order to improve the coverage in a shopping mall, FAPs are deployed. The shopping mall owner may have been provided a special deal by the network operator where the employees of the shopping mall will get preferential charging rates and priority access when accessing services via these FAPs. In exchange, the shopping mall owner allows the public to use the FAPs to access the normal network operator services. The FAP Hosting Party should not need to manage the public access and the public should not need to do anything special in order to get services on the FAP.

Use case-10: Open access mode

Typically, employed to enhance coverage or capacity of an operator’s public network, for example in railway stations, airports, stadiums, etc., taking benefit of the FAPs additional functionality (e.g. uncoordinated deployment).

Use case-11: FAP interacts with Home network

User A connects with his UE (possibly a pre-Rel 9 “legacy” UE) to the FAP with IMS Interworking and Local IP Access to the home network capabilities. The home network accommodates home
network devices (intercom, door lock, network radio, photo server, etc.) and the FAP. User A should be able to communicate with a visitor at intercom via the mobile device.

**Use case-12: FAP interacts with IP-PABX**

User A connects with his UE (possibly a pre-Rel 9 “legacy” UE) to a FAP with IMS Interworking and Local IP Access to the home network capabilities at an office. The FAP might be deployed and interconnect with an enterprise extension telephone system (e.g. SIP based PABX). User A should be able to make/receive an extension call to/from fixed line UE under SIP based PABX. In addition, User A with the mobile device and User B with computers should be able to access a common groupware server at the office and share the same information such as schedule, emails, etc.

**Use case-13: Electronic customer guide in shopping centre, using local IP access**

A department store or shopping centre provides electronic shopping guide. When user A enters into a shopping centre where a shopping centre FAP is installed, an invitation indication shows up on his mobile device which he accepts. This allows him access to the centre’s FAP. Subsequently, he accesses the centre’s customer service server, which is only accessible through the FAP where he uploads his shopping list. The customer service server responds a list of sale items of similar nature. He accepts or declines the various choices and the final shopping list is downloaded to his UE. While user A is waiting, User A watches free TV show or advertisement provided through the FAP for the shop customer. While in the shopping centre the user has simultaneous access to operator’s and local shopping centre services.

**Use case-14: Local IP access**

The user has the subscription through home operator H. The user is served by the home operator H. The UE obtains IP connectivity in both a local gateway to obtain local connectivity for IMS services (e.g. as in local IP access or for enterprise scenarios with call to other terminals in the PABX area) and to a home gateway (as in normal connectivity for IMS services). For IMS sessions to be routed to e.g. remote terminals, the traffic is sent through the connectivity with the home gateway, whereas for IMS session that can be routed locally (e.g. based on local phone number), the traffic is sent through the connectivity with the local gateway through the local IP access. Whether the UE routes a specific IMS session through the local access or the home gateway, it can be controlled on a per session basis. Also, the UE may obtain local connectivity by default (e.g. based on static configuration by the operator) or dynamically based on indication by the IMS server.

**Use case-15**

Subscriber A from Network A owns FAP A because of no macro network coverage. Guest user B from Network B visits subscriber A’s house. Subscriber A wants to allow guest user B access to FAP A while the guest user B is visiting.

**Use case-16**

Corporation A has sites in country A, B and C. Corporation A has employees from country A and B. Employees in country A are from Operator AA and AB. Employees in country B are from Operator B. Corporation A has FAP in country A from Operator AA and country B from Operator B. Employees from country A and B are allowed access to FAPs in country A and B.

### 2.5 Use cases as defined in WiMAX

Here we present use cases for WiMAX, as introduced in [ARI09]:

**2.5.1 Handover**

This use case illustrated by Figure 22 refers to a scenario when a subscriber initiates a session in a macro/femto network and then moves to a different femto/macro network of the same service provider with a seamless session transfer.
2.5.2 Non-Interference with macro coverage area

This use case illustrated by Figure 23 describes a scenario in which a subscriber deploys a FAP at his home, which is not covered by his service provider (other service providers can be present in the area). In this use case it is generally expected that the FAP does not radiate any RF, because it is not licensed in the coverage area of other service providers. However, it is possible to do so if it is specified by the licensing agreement between operators in that area.

2.5.3 Inter-RAT (Radio Access Technology) Session Continuity

This use case refers to a scenario where a subscriber is accessing a service over a WiFi network and, for the purpose of increasing the quality of service, the subscriber decides to switch the session to the macro network. It is expected that FAP in coordination with the core network facilitates session handover.
2.5.4 Visitor/Guest Access

This use case illustrated by Figure 25 refers to a scenario such that a subscriber has a FAP installed at his home and a guest (belonging to the same service provider) tries to access the FAP. Here, it is expected that the FAP is configurable to allow visitors/guests to access services through the FAP. This kind of situation can apply either in the household deployment, either in the public environment deployment, or an office deployment with several users accessing in different time of day.
3 OPERATIONAL SCENARIOS

In the previous section, the scenarios and use cases are described, rather at a high level. This section provides additional technical details about the definition of scenarios.

3.1 Deployment

Although rural deployment may be considered, the Femto Forum considers dense-urban and suburban deployments as defined in the twofold subsections.

3.1.1 Dense-urban model

Blocks of apartments are dropped into the three center cells of a macro cell layout with ISD (Inter-Site Distance) of 1 km. Each block is 50×50m and consists of 2 buildings (north and south) and an east-west street between them. The width of the street is 10m. Each building has from 2 to 6 floors. In each floor there are 10 apartment units in two rows of five. Each apartment is 10x10m and has a one-meter-wide balcony. The minimum separation between two adjacent blocks is 10m. The probability that the FUE is in the balcony is 0.1. In each cell there are 2000 apartment units, corresponding to 6928 households per km². There is assumed a 4.8% FAP penetration which means 96 of 2000 apartments in each cell have a FAP installed at home. 25% of these (24) are simultaneously active. If a FAP is active, it transmits at full power; otherwise it transmits only the pilot and overhead channels. MUEs are also dropped randomly into the three center cells of the 57-cell macro layout such that 30% of the MUEs are indoor. In this deployment, a 3GPP micro-urban model is used for outdoor path loss computation;

3.1.2 Suburban model

Houses of size 12x12m are dropped in the three center cells of a 57-cell macro layout with ISD of 1km. In each house there is one FAP. The probability that the FUE is inside the house is 0.8 and the probability that the FUE is outside the house in the yard is 0.2. The total lot size is 24x24m. The houses do not overlap and no FUE is inside a neighbour’s house. Then, the MUEs are dropped in the three center cells of the macrocell layout such that each MUE is inside a house with probability 0.3. There is 99 FAPs per macrocell. Out of these 24 FAPs are simultaneously active. A 3GPP macro-urban model for the outdoor path loss computation is used.

3.1.3 Additional characteristics

Additional characteristics related to deployment could be defined:

- User density

The first key difference between these environments is the user density. In [FEM-INT08] the following figures are assumed. In the evaluation of the performance of the network of a given operator, a certain market² share needs to be assumed. Typical market shares are obtained from [ROC1D5].

<table>
<thead>
<tr>
<th></th>
<th>Rural</th>
<th>Suburban</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential User density (persons/km²)</td>
<td>100</td>
<td>1000</td>
<td>6000</td>
</tr>
<tr>
<td>Residential Household Density (houses/km²)</td>
<td>40</td>
<td>360</td>
<td>2300</td>
</tr>
<tr>
<td>SME employees density (persons/km²)</td>
<td>40</td>
<td>350</td>
<td>2000</td>
</tr>
<tr>
<td>Market share</td>
<td>53.4%</td>
<td>27.2%</td>
<td>19.4%</td>
</tr>
</tbody>
</table>

Table 4: User densities in urban, sub-urban and rural deployment scenarios

Other relevant parameters, such as the cell size, backhauling and TX/RX sites are based on [ROC1D1].

² The market share is the fraction of users associated to a certain operator.
• **Cell size**

Due to the different user density, the deployment in urban environment is typically capacity-limited, whereas in rural environment it is coverage-limited. Cell sizes depend on a lot of parameters; typically macrocells range from a few hundred meters for an urban microcell to several kilometres for a rural macrocell and femtocells range from a few meters to tens of meters (depends of type of deployment e.g. urban/rural domestic, corporation etc). Naturally, the cell size has a direct impact on the propagation channel (e.g. a larger cell means a larger delay spread and higher signal attenuation) and capacity of the system (reuse of frequencies). For the same territory, smaller cells sizes cause higher number of cells (cellular structure of the macro network). Femtocells due to their small sizes increase significantly capacity of the network.

• **Backhauling**

The backhaul can be represented as a wired link (e.g. optical fiber) or can rely on microwave dedicated link, especially in rural environments. The backhaul of the macro network is maintained by the operator, and so is fully controlled. In femto network the backhaul link is of great importance since is based on the subscriber internet connection (e.g. xDSL, dedicated link) and thus, in general, not controlled by the operator. Many conditions have to be made on the femto backhauling since the QoS has to be fulfilled independently of type of the network – macro or femto.

• **Transmission/ Reception Sites**

In cities, macro BS may be mounted on towers on top of buildings, micro BSs are typically mounted on rooftops and RSs can be either mounted on rooftops or on lamp-posts. In rural areas, macro BSs are mounted on towers and it is likely that RSs will also be mounted on towers in order to provide a sufficient coverage extension. In both urban and rural environments the end user may be located indoor, and therefore the outdoor-to-indoor penetration loss shall be included in the path loss. The installation of an external (e.g. rooftop-mounted) reception antenna may also be considered in rural areas with a negative impact on the equipment acquisition and installation cost. Femto BS are low power BS that are located indoor in a not controlled manner (defined by end users). Basically, they are connected with indoor users and due to very short distances guarantee very high data rates (very low propagation losses). The important issue is linked to the relation between locations of macro BS and FAPs, and also between FAPs.

3.1.4 **Geographical deployment**

Leveraging on the analysis performed in [ROC1D1], the addressable markets have been identified as Urban, Suburban and Rural. Those areas are characterised by the number of the so-called NUTS5 (Nomenclature of Unity Territorial Statistic – category 5 being a commune) and their size or, in other words, the population density.

- **Population density in Rural areas**: all the NUTS 5 (or equivalent) with a population density lower than 100 Inhats/km² (there is a mean of 33 inhabitant per NUT5 in France)

- **Population density in Suburban areas**: all the NUTS 5 (or equivalent) with a population density between 100 and 500 Inhats/km²

- **Population density in Urban areas**: all the NUTS 5 (or equivalent) with a population density greater than 500 Inhats/km².

3.1.5 **Multi FAP deployment**

The multi FAPs deployment is derived from the real deployment of family houses at the fringe of the town. For the sake of simplicity, the houses are regularly spaced along both sides of the street. Only one FAP is assumed per house. Furthermore, two macro BSs are deployed symmetrically behind the
houses. The UEs moves directly along the street until it reach the end of it. The $x$ position (position according $x$ axis) of the UE is select either randomly or the UEs are placed in regular distances over the whole width of the street. Also the $y$ position of the UE can be selected by the two ways. The first one is a random drop of the UE at beginning of the simulation. The UE is moving along the street until it reaches the end and then it is no longer considered in simulation (connection to the macro BS is assumed). It results into the decreasing number of UEs during the simulation. In the second case, all UEs starts at the zero $y$ position ($y = 0$ m). All of them are equally increasing the $y$ position according to the UE speed. The number of UEs is constant over all simulation time.

Also the non-symmetrical scenario with only one BS and half of the houses can be considered (in Figure 26, the half from the UE position to the left).

The deployment of FAPs and MBSs (including the most important simulation parameters) for handover evaluation is depicted in Figure 26.

![Figure 26. FAPs and BSs deployment for handover evaluation](image)

The range on individual parameters and typical values assumed for evaluation are presented in Table 5

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$FAP$ transmit power</td>
<td>10 - 21dBm</td>
<td>15 dBm</td>
</tr>
<tr>
<td>$FAP_Dist_X$</td>
<td>5 – 25 m</td>
<td>15 m</td>
</tr>
<tr>
<td>$FAP_Dist_Y$</td>
<td>10 – 50 m</td>
<td>30 m</td>
</tr>
<tr>
<td>Street Width</td>
<td>5 – 20 m</td>
<td>8 m</td>
</tr>
<tr>
<td>Street Length</td>
<td>500 – 2000 m</td>
<td>1000 m</td>
</tr>
<tr>
<td>BS transmit power</td>
<td>36 – 46dBm</td>
<td>36 dBm</td>
</tr>
<tr>
<td>Distance of BS and middle of the street</td>
<td>500 – 1500 m</td>
<td>500 m / 1000 m</td>
</tr>
<tr>
<td>UE transmit power</td>
<td>23 dBm</td>
<td>23 dBm</td>
</tr>
<tr>
<td>UE speed</td>
<td>1 – 3 m/s (pedestrian)</td>
<td>1 m/s</td>
</tr>
<tr>
<td>UE mobility model</td>
<td>Direct movement (see section 5.11.1)</td>
<td>DM</td>
</tr>
</tbody>
</table>

Table 5. Parameters for simulation of Multi-FAPs deployment.

### 3.1.6 Relay-assisted vs. FAP-based deployment

The most recent tendencies in wireless communications point towards the definition of new cellular architectures able to overcome the tradeoff between coverage and capacity. Among them, RS-assisted
deployments and FAP-based deployments have raised worldwide research efforts. It is therefore natural to think of methodologies to compare them in a fair way so that some recommendations could be extracted in terms of which one is more economically efficient for an operator.

It should be noted that in both cases the goal is to combat the pathloss and shadowing attenuation by deploying additional terminals, so they could be competing technologies. However, relay-based deployments cannot compete in principle with femtocell deployments for three reasons:

- Increased utilisation of radio resources due to half-duplexing at the RS.
- Additional bandwidth granted to FAP through wired in-home connections.
- Poor outdoor-to-indoor penetration for transmissions from RS.

On the other side, relays could be beneficial if a sufficiently high density deployment is done, so that indoor outage areas are reduced. This would establish a threshold below which subscribers are not motivated to the adoption of a FAP. Although initial studies recommended a density of in-cell relay deployment which is much lower than the expected FAP density [ROC1D5], these were done mainly for outdoor coverage.

Complementarity of RS deployments and FAP-based deployments can also be envisioned considering a different point of view: the deployment of FAP implies BS traffic off-loading, a lower-density requirement of BS and hence outdoor coverage-limited (rather than capacity-limited) deployments. In this situation, the spectral efficiency of the cell is larger than the offered traffic which implies economical inefficiency which could be solved by deploying RS that give service to coverage holes in outdoors.

In both cases, the presence of RS induces additional interference that may limit the performance of FAP. As a consequence, there is interplay between the density of BS, FAP and RS that is worth being studied.

### 3.1.6.1 Methodology

The methodology adopted in ROCKET based on indifference plots [ROC1D5][ROC3D1] will be considered here. We are interested in giving a response to the following questions:

- Which density of BS and RS provides overall outage and capacity levels that do not require deployment of FAP? How economical is this solution?
- Given a certain density of FAP, what is the optimum-cost required density of BS and RS for a certain total outdoor capacity and outage rate?

The answers will depend on the associated business model adopted and many economical parameters associated to the deployment, among them the most important is the relative costs of BS, RS and FAP and backbone associated costs.

The impact of cross-tier interference has to be taken into account, along with the algorithms proposed in WP3 for its mitigation and management. Some kind of high-level interface will be needed to incorporate these algorithms to the system level simulator.

Simulating conditions include:

- A single macro-cell taking into account the interference from other macro-cells (system-level simulations)
- Femtocells are to be deployed under a uniform or predefined pattern
- Designs will be based on the mutual information (or lower bounds of it) in order to capture practical constraints of coded transmissions
Matlab-based simulation platform

3.1.6.2 Assumptions on relay terminals

The relay-based protocols will be selected from the extensive studies done during the EC project ROCKET [ROC3D1]. The following realistic assumptions are appointed:

- Relays are half-duplex terminals
- Higher transmitted power than FAP
- Outdoor operation
- Interference between RS and FAP not be negligible

3.1.6.3 Scenarios for comparison

The most relevant usage scenarios for relaying networks were studied in ROCKET [ROC1D1]. We will reduce them to two: outdoor to indoor coverage, outdoor coverage holes and coverage extension at cell edges:

- Fixed RS in scenarios B and E are deployed to improve per user throughput in areas not sufficiently covered, due to shadowing, indoor or underground coverage. Relay stations are placed in over-the-roof positions so that a good quality link to the BS is provided.
- Fixed RS in scenario C are deployed to provide coverage to areas beyond the cell edge. Relays can be either transparent or non-transparent. Relay stations are placed in over-the-roof positions so that a good quality link to the BS is provided.

A single cell scenario deployment of relay stations is considered by FREEDOM, which will include the impact of the nearby cells. In single cell scenarios it is assumed that one base station is serving a number of relays, and to that end, it is assisted by one or many relay stations.

![Figure 27. Relay-based scenarios in ROCKET. Only scenarios B, C and E will be adopted in FREEDOM for RS vs FAP-based comparison](image-url)
3.2 Deployment architectures

3.2.1 WiMAX architecture

3.2.1.1 Baseline architecture

IEEE 802.16 standards provide specifications for the air interface for WiMAX but do not define the full end-to-end WiMAX network. The WiMAX Network group has developed a network reference model to serve as an architecture framework for WiMAX deployments. Figure 28 shows a simplified illustration of an IP-based WiMAX network architecture.

In this model the more important functional entities are:

- **BS**: The BS is responsible for providing the air interface to the MS. It embodies a full instance of the WiMAX MAC and PHY in compliance with the IEEE 802.16 suite of applicable. It incorporates scheduler functions for uplink and downlink resources, which will be left for vendor implementation.

- **Access service network gateway (ASN-GW)**: The ASN gateway typically acts as a layer 2 traffic aggregation point. A BS may be logically connected to more than one ASN-GW to allow load balancing and redundancy options.

- **Connectivity service network (CS)**: It provides IP connectivity and all the IP core network functions. The CSN may further comprises network elements such as routers, AAA proxy/servers, home agent, and user databases as well as interworking gateways or enhanced broadcast services and location-based services.

The WiMAX architecture framework allows for the flexible decomposition and/or combination of functional entities when building the physical entities. For example, the ASN may be decomposed into base station transceivers (BST), base station controllers (BSC) and an ASN-GW. It is also possible to collapse the BS and ASN-GW into a single unit, which could be thought of as a WiMAX router.

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Figure 28. WiMAX network reference architecture [Cisco-05]
In addition to functional entities, the WiMAX Forum network working group defines interfaces, referred to as reference points, between these entities:

- **R1**: Interface between MS-ASN. In addition to the air interface, it includes protocols in the management plane.
- **R2**: Interface between MS-CSN. It provides authentication, service authorization, IP configuration and mobility management.
- **R3**: Interface between ASN-CSN to support policy enforcement and mobility management.
- **R4**: Interface between ASN-ASN to support inter-ASN mobility.
- **R5**: Interface between CSN-CSN to support roaming across multiple network service providers (NSPs).
- **R6**: Interface between BS and ASN-GW. It consists of a set of controls and protocols for communication between the BS and the ASN GW. These include intra-ASN- data path or inter-ASN tunnels between the BS and ASN GW. The control plane on the other hand includes protocols for IP tunnel management (establish, modify and release) in accordance with the MS mobility events. R6 may also serve for exchange of MAC state information between neighboring BSs.
- **R8**: Interface between BS-BS. It consists of a set of control plane message flows and in some situations, bearer plane data flow between the base stations to ensure fast and seamless handover. Control plane consists of the inter-BS communication protocol defined in IEEE 802.16 and additional set of protocols that allow controlling the data transfer between the Base Stations involved in handover of certain MS. Bearer plane consists of protocols that allow the data transfer between BSs involved in handover of certain MS.

### 3.2.1.2 Relaying in 802.16m

IEEE 802.16j specifications initially defined 802.16 multihop relay capabilities and functionalities of interoperable relay stations and base stations with the purpose of enhancing coverage, throughput and system capacity of 802.16 networks. The next evolution, IEEE 802.16m, aimed to provide performance improvements necessary to support future advanced services and applications, such as those described by the ITU in Report ITU-R M.2072, including also relay-based transmissions.

Relaying in IEEE 802.16m is performed using the decode-and-forward paradigm. While the base stations and relay stations deployed within a sector operate using either time division duplexing (TDD) or frequency division duplexing (FDD) of DL and UL transmissions, the relay station operates in time-division transmit and receive (TTR) relaying mode.

Two basic modes of operation are considered for relay stations: transparent or non-transparent mode. In the transparent case, the relay station that does not transmit control information such as preamble, super-frame header or MAPs that describe frame composition in a scheduling interval. A non-transparent relay is a relay station that transmits this information, and hence it has some layer-2 capabilities. While a BS can support the co-existence of the transparent and the non-transparent relay stations, transparent relaying is limited to the scenario where the superordinate station is a non-transparent relay or a base station.

The frame structure is different in both cases. In the transparent relay case, the DL subframe starts with the RS receiving from superordinated stations, i.e. BSs or non-transparent RSs. A DL Access Zone follows, where the BSs or RSs transmit to MSs.

For a non-transparent relay, the frame starts with a DL Access Zone, where the RS (or BS) transmits to MS. Preambles, headers and unicast transmissions are placed in this zone. A DL Transmit Zone follows where the relay may transmit to subordinated RSs or MS. In the last zone, the RS receive from superordinated BSs or RSs. When more than two hops are considered, the relay station corresponding to the even hop exchanges the allocation of the last two sections: first, the relay receives from
superordinated stations, and then the relay transmit to subordinated RSs or MS. Note that, even if only two hops are considered, the transmission of one packet spans over two frames, while for transparent relays the first and second hop transmissions can be carried out within a single frame.

The UL subframe configuration is the same for both transparent or non-transparent relays. It starts with the RS receiving from subordinated RSs or from MSs in the uplink (UL receive zone). It follows with the RS transmitting to superordinated stations (BSs or RSs). When more than two hops are considered, the relay station associated to the even hop exchanges the allocation of the last two sections: first, the relay transmits two superordinated stations, and then the relay receives from subordinated RSs or MS.

A non-transparent RS may operate in distributed or centralized scheduling. When a BS is configured to operate in centralized scheduling, the BS schedules all radio resources in its cell. In distributed scheduling, each station (BS or RS) schedules the radio resources on its subordinate link within the radio resources assigned by the BS. The BS may exercise additional control over the scheduling of its RSs.

802.16m considers also cooperative relaying as a technique whereby either the BS and one or more RSs, or multiple RSs cooperatively transmit or receive data to/from one subordinate station or multiple subordinate stations. Cooperative relaying may also enable multiple transmitting/receiving stations to partner in sharing their antennas to create a virtual antenna array.

For deployments involving IEEE 802.16m RSs (ARS, Advanced RS) and legacy RS, Figure 29 indicate the specific IEEE 802.16 protocol to be used for supporting a particular interface.

![Figure 29. Relay related connections [IEEE802.16m_SDD]](image)

3.2.2 LTE and E-UTRAN architecture

3.2.2.1 Baseline architecture

In UMTS 3G, UTRAN (Universal Terrestrial Radio Access Network) Architecture, the NodeB (base station) connects to a RNC through the Iub interface. Among other functions, the RNC buffers the original IP packets and performs header compression (HC), Ciphering and Outer ARQ. HARQ, on the other hand, is performed at NodeB.
For LTE, Evolved UTRAN is considered where the Node B is substituted by the eNB. The E-UTRAN consists of eNBs, providing the E-UTRA user plane (PDCP/RLC/MAC/PHY) and control plane (RRC) protocol terminations towards the UE. The RNC is no longer considered. The outer ARQ, which is carried out by the RNC in UMTS, is performed now at the eNB.

More specifically the eNB performs the following functions:

- Terminates RRC, RLC and MAC protocols and takes care of Radio Resource Management Functions (admission control, scheduling, etc.)
- Selects MME (Mobility Management Entity) at UE attachment when no routing to an MME can be determined from the information provided by the UE
- Schedules and transmits paging messages coming from MME
- Schedules a transmit broadcast information coming from MME and O&M
- Decides measurement report configuration for mobility and scheduling
- Does IP header compression and encryption of user data streams
- Routing of User Plane data towards Serving Gateway

The eNBs are connected by means of the S1 interface to the EPC (Evolved Packet Core), more specifically to the MME (Mobility Management Entity) by means of the S1-MME and to the Serving Gateway (S-GW) by means of the S1-U. The S1 interface supports a many-to-many relation between MMEs / Serving Gateways and eNBs. The eNBs are interconnected with each other by means of the X2 interface. Whilst logically representing a point to point link between eNBs, the physical realisation need not be a point to point link.

![E-UTRAN Architecture][1]

### 3.2.2.2 X2 Interface description

As the interface X2 plays an important role in the exchange of control plane information between MBS and FAP, a quick overview of such interface is provided in the following.

Several 3GPP documents cover different aspects for X2 interface:

- The physical technologies to support the X2 interface are covered by [3GPP TS 36.421].
- The transport of signalling messages across X2 interface is described in [3GPP TS 36.422]
- The network layer signalling procedures of the control plane and messages between eNBs are described in [3GPP TS 36.422]
The standards for user data transport protocols are covered in [3GPP 36.424]

Among the functions on the X2 interface are:

- Intra LTE-Access-System Mobility Support, to hand over a certain UE to another eNB, including forwarding of user plane data, status transfer and UE Context Release.
- Load Management to exchange information among eNBs regarding resource status, overload and traffic load. These information exchanging is essential for the implementation of coordination techniques and interference aware resource allocation.

**Functions and related procedures**

The following table illustrates the mapping between the X2-AP (Application Protocol) and X2AP Elementary Procedures (from [3GPP TS 36.423])

<table>
<thead>
<tr>
<th>Function</th>
<th>Elementary Procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mobility Management</strong></td>
<td>a) <strong>Handover preparation</strong>: Establish necessary resources in an eNB for an incoming handover</td>
</tr>
<tr>
<td></td>
<td>b) <strong>Sequence Number (SN) status transfer</strong>: Transfer the Packet Data Convergence Protocol (PDCP) SN and Hyper Frame Number (HFN) receiver/transmitter status for uplink/downlink from the source to the target eNB during an X2 handover</td>
</tr>
<tr>
<td></td>
<td>c) <strong>UE context release</strong>: It is initiated by the target eNB to indicate the source eNB that radio and control plane resources for the handed over UE context are allowed to be released</td>
</tr>
<tr>
<td></td>
<td>d) <strong>Handover cancel</strong>: Enable a source eNB to cancel an ongoing handover preparation or an already prepared handover</td>
</tr>
<tr>
<td><strong>Load Management</strong></td>
<td>a) <strong>Load indication</strong>: Transfer load and interference co-ordination information between eNBs controlling intra-frequency neighbouring cells</td>
</tr>
<tr>
<td></td>
<td>b) <strong>Resource Status Reporting Initiation</strong>: It is used by an eNB to request the reporting of load measurements to another eNB.</td>
</tr>
<tr>
<td></td>
<td>c) <strong>Resource Status Reporting</strong>: To report the result of measurements required by another eNB in the resource status reporting initiation.</td>
</tr>
<tr>
<td><strong>Reporting of General Error Situations</strong></td>
<td>The <strong>Error Indication procedure</strong> is initiated by an eNB to report detected errors in one incoming message</td>
</tr>
<tr>
<td><strong>Resetting the X2</strong></td>
<td>The purpose of the <strong>Reset procedure</strong> is to align the resources in eNB1 and eNB2 in the event of an abnormal failure. The procedure resets the X2 interface.</td>
</tr>
<tr>
<td><strong>Setting up the X2</strong></td>
<td>The purpose of the <strong>X2 Setup procedure</strong> is to exchange application level configuration data needed for two eNBs to interoperate correctly over the X2 interface. The initiating eNB may include the Neighbour Information information element (IE) in the X2 SETUP REQUEST message. The candidate eNB may also include the Neighbour Information IE in the X2 SETUP RESPONSE message. The Neighbour Information IE shall only include E-UTRAN cells that are direct neighbours of cells in the reporting eNB.</td>
</tr>
<tr>
<td><strong>eNB Configuration Update</strong></td>
<td>a) <strong>eNB Configuration Update procedure</strong>: Update application level configuration data needed for two eNBs to interoperate correctly over the X2 interface.</td>
</tr>
<tr>
<td></td>
<td>b) <strong>Cell Activation</strong></td>
</tr>
<tr>
<td><strong>Mobility Parameters Management</strong></td>
<td><strong>Mobility Settings Change</strong>: To negotiate the handover trigger settings with another eNB controlling neighbouring cells</td>
</tr>
</tbody>
</table>
Mobility Robustness Optimisation

a) **Radio Link Failure Indication**: Transfer information regarding RRC re-establishment attempts between eNBs controlling neighbouring cells.

b) **Handover Report**: Transfer mobility related information between eNBs controlling neighbouring cells.

Energy Saving

a) **eNB Configuration Update**

b) **Cell Activation**: To request to a neighbouring eNB to switch on one or more cells, previously reported as inactive due to energy saving reasons.

| Table 6. Mapping between the X2-AP (Application Protocol) and X2AP Elementary Procedures |

**Messages through X2**

The following table lists all the messages defined to support the above described procedures ([3GPP TS 36.423]).

<table>
<thead>
<tr>
<th>Message</th>
<th>Direction</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Handover Request</strong></td>
<td>source eNB → target eNB</td>
<td>To request the preparation of resources for a handover</td>
</tr>
<tr>
<td><strong>Handover Request Acknowledge</strong></td>
<td>target eNB → source eNB</td>
<td>To inform the source eNB about the prepared resources at the target.</td>
</tr>
<tr>
<td><strong>Handover Preparation Failure</strong></td>
<td>target eNB → source eNB</td>
<td>To inform the source eNB that the Handover Preparation has failed</td>
</tr>
<tr>
<td><strong>SN Status Transfer</strong></td>
<td>source eNB → target eNB</td>
<td>To transfer the uplink/downlink PDCP SN and HFN status during a handover</td>
</tr>
<tr>
<td><strong>UE Context Release</strong></td>
<td>target eNB → source eNB</td>
<td>To indicate that resources can be released</td>
</tr>
<tr>
<td><strong>Handover Cancel</strong></td>
<td>source eNB → target eNB</td>
<td>To cancel an ongoing handover</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Message</th>
<th>Direction</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Load Information</strong></td>
<td>eNB1 → eNB2</td>
<td>To transfer load and interference co-ordination information</td>
</tr>
<tr>
<td><strong>Error Indication</strong></td>
<td>eNB1 → eNB2</td>
<td>To indicate that some error has been detected in the eNB</td>
</tr>
<tr>
<td><strong>X2 Setup Request</strong></td>
<td>eNB1 → eNB2</td>
<td>To transfer the initialization information for a TNL association</td>
</tr>
<tr>
<td><strong>X2 Setup Response</strong></td>
<td>eNB2 → eNB1</td>
<td>To transfer the initialization information for a TNL association</td>
</tr>
<tr>
<td><strong>X2 Setup Failure</strong></td>
<td>eNB2 → eNB1</td>
<td>To indicate X2 Setup failure</td>
</tr>
<tr>
<td><strong>Reset Request</strong></td>
<td>eNB1 → eNB2</td>
<td>To request the X2 interface between the two eNB to be reset.</td>
</tr>
<tr>
<td><strong>Reset Response</strong></td>
<td>eNB2 → eNB1</td>
<td>Response to a RESET REQUEST message</td>
</tr>
<tr>
<td><strong>eNB Configuration Update</strong></td>
<td>eNB1 → eNB2</td>
<td>To transfer updated information for a TNL association</td>
</tr>
<tr>
<td><strong>eNB Configuration Update Acknowledge</strong></td>
<td>eNB2 → eNB1</td>
<td>To acknowledge update of information for a TNL association</td>
</tr>
<tr>
<td><strong>eNB Configuration Update Failure</strong></td>
<td>eNB2 → eNB1</td>
<td>To indicate eNB Configuration Update Failure</td>
</tr>
<tr>
<td><strong>Resource Status Request</strong></td>
<td>eNB1 → eNB2</td>
<td>To initiate the requested measurement according to the parameters given in the message.</td>
</tr>
<tr>
<td><strong>Resource Status Response</strong></td>
<td>eNB2 → eNB1</td>
<td>To indicate that the requested measurements are successfully initiated</td>
</tr>
<tr>
<td><strong>Resource Status Failure</strong></td>
<td>eNB2 → eNB1</td>
<td>To indicate requested measurements cannot be initiated</td>
</tr>
<tr>
<td><strong>Resource Status Update</strong></td>
<td>eNB2 → eNB1</td>
<td>To report the results of the requested measurements</td>
</tr>
<tr>
<td><strong>Mobility Change Request</strong></td>
<td>eNB1 → eNB2</td>
<td>To initiate adaptation of mobility parameters</td>
</tr>
<tr>
<td><strong>Mobility Change Acknowledge</strong></td>
<td>eNB2 → eNB1</td>
<td>To indicate that the eNB2 Proposed Mobility Parameter proposed by eNB1 was accepted</td>
</tr>
</tbody>
</table>
Mobility Change Failure | eNB₂ → eNB₁ | To indicate that the eNB₂ proposed Mobility Parameter proposed by eNB₁ was refused
--- | --- | ---
Radio Link Failure (RLF) Indication | eNB₂ → eNB₁ | To indicate a RRC re-establishment attempt by a UE that was previously attached to eNB₁
Handover Request | eNB₁ → eNB₂ | To report a handover failure event
Cell Activation Request | eNB₁ → eNB₂ | To request a previously switched-off cell/s to be re-activated
Cell Activation Response | eNB₂ → eNB₁ | To indicate that one or more cell(s) previously switched-off has(have) been activated.
Cell Activation Failure | eNB₂ → eNB₁ | To indicate cell activation failure

Table 7. Messages defined to support the procedures described in Table 6

Freedom is interested in messages designed for the exchange of appropriate information between eNBs for interference mitigation. As indicated above, such information is sent through the load information message which is sent by an eNB to neighbouring eNBs. In order to support coordination in the uplink, the load information message contains the following IEs for a cell² controlled by the eNB originating the message (a maximum of 256 cells can be served by an eNB):

- **Uplink Interference Overload Indication**: This IE indicates the interference level (high, medium, low,…) experienced by the cell at each physical resource block. A maximum of 110 physical resource blocks are possible.
- **Uplink High Interference Indication**: This IE indicates the occurrence of high interference as seen by the sending eNB. For each physical resource block (up to 110), it takes two possible values: ‘1’ indicating ‘high interference sensitivity’ and 0 indicating ‘low interference sensitivity’. The target cell identifier for which the high interference indication is meant is also indicated in this IE.

The interaction between both information elements is implementation specific.

For interference aware scheduling in the downlink, the load information message includes also the relative narrowband transmission power (RNTP) information. The RNTP indicates, per physical resource block, if the transmission power is not exceeding the defined RNTP threshold (in such a case a 0 is sent) or, on the opposite, ‘no promise on the transmission power is given’ (in such a case a 1 is sent).

From the coordination point of view, another useful message is the resource status update message that includes, for each eNB controlled cell, information about hardware load (low load, medium load, high load, overload) and usage of physical resource blocks in both downlink and uplink.

### 3.2.2.3 Support for femtocells in LTE-A

When HeNBs are considered, the E-UTRAN architecture may deploy a Home eNB Gateway (HeNB GW) to allow the S1 interface between the HeNB and the EPC to scale in order to support of a large number of HeNBs. The HeNB GW appears to the MME as an eNB. The HeNB GW appears to the HeNB as an MME.

The HeNB GW shall connect to the EPC in a way that inbound and outbound mobility to cells served by the HeNB GW shall not necessarily require inter MME handovers. One HeNB serves only one cell. The S1 interface between the HeNB and the EPC is the same whether the HeNB is connected to the EPC via a HeNB GW or not. X2 connectivity of HeNBs is not currently supported in the standard.

² Cell identifiers are given by 28 bits, where the 20 leftmost bits correspond to the controlling Macro eNB identifier. If a Home eNB is controlling the cell, then all the 28 bits in the cell identifier are the same as the Home eNB identifier.
As X2 connectivity of HeNBs is not supported in the standard, DOCOMO proposed to modify E-UTRAN architecture by extending the X2 interface to the HeNB and therefore supporting interference signalling between eNB’s and HeNB’s.

The following figure illustrates the proposal by DOCOMO [3GPP R4-093244]. For HeNB’s connected via HeNB GW the X2 interface is extended to the HeNB. The HeNB GW receives messages from eNB’s via the X2 interface and forwards the message to the recipient denoted in the message header. HeNB’s directly connected to the MME / S-GW may either have a direct X2 connection to nearby eNB’s or an X2 connection to the HeNB GW. In the former case, HeNB and eNB’s exchange messages directly via X2.

### 3.2.2.4 Relaying in LTE-A

LTE-A standard considers also relaying as a tool to system enhancement in terms of high data rates coverage, group mobility, temporary network deployment, the cell-edge throughput and/or provision of coverage in new areas. The relay node is wirelessly connected to radio-access network via a donor cell. The connection can be
In-band, in which case the network-to-relay link share the same band with direct network-to-UE links within the donor cell. Rel-8 UEs should be able to connect to the donor cell in this case.

- Out-band, in which case the network-to-relay link does not operate in the same band as direct network-to-UE links within the donor cell

Relays can also be classified into transparent and non-transparent relaying, which entails different complexity at the UE:

- Transparent, in which case the UE is not aware of whether or not it communicates with the network via the relay.
- Non-transparent, in which case the UE is aware of whether or not it is communicating with the network via the relay.

Despite the definition is slightly different to the one in 802.16, the implications are the same. Finally, in a similar way to the one considered in 802.16 for centralized and decentralized relaying, in LTE-A it is considered that a relay may

- be part of the donor cell
- control cells of its own

3.3 Mobility and handover

Generally, four handover scenarios are taken into account as depicted in Figure 33. The first one, hand-in, refers to scenario where a MS performs handover from macrocell to femtocell. The second scenario represents the case of handover from femtocell to macrocell. This is entitled hand-out. The third scenario, inter-FAP, corresponds to the case when a MS executes handover from one femtocell to another one. Last case of handover corresponds to a vertical handover. It means the handover between FAPs based on the different technologies (e.g. LTE-A and UMTS).

![Figure 33. Overview on the handover scenarios](image)

The hand-in as well as hand-out enables handover between macro and femto cells. Therefore, the exchange on MAC management messages between FAP and macro BS is assumed also over the DSL/fibre backbone.

Two possibilities can be distinguished for the inter-FAP handover. The first one assumes both FAPs served by the same service provider and both FAPs placed at the same location (e.g. same house), however at different places (e.g. different floors). It means that both FAPs are connected via same...
gateway into the backbone. The second case of the inter FAP handover corresponds to the situation when the open or at least hybrid access is enabled. In this case, the UE performs handover among FAPs of different users.

The handovers are not limited only to the switching among the AS based on the same technology, however, also the support of different 3GPP standards are taken into account.

The above mentioned handover scenarios covers also the case when the RSs are deployed. Then, the hand in/out between a FAP and RS can be also executed. This handover is analogical to the hand in/out between FAP and macro BS. Only fixed RSs are considered.

Two handover strategies can be applied to trigger the handover i.e. proactive and reactive handover

**Proactive Handover**

In the proactive handover scenario, the handover may occur any time before the level RSSI of current BS reaches the handover hysteresis margin (HM). The proactive handover strategy attempts to estimate network characteristics of a specific position before the MS reaches that position. Assumed the MS discovered that the new target BS’ RSSI (or FAP’s RSSI) overpasses the origin one from its serving BS/FAP. The MS calculates the time left before the normal handover is triggered, then triggering the handover earlier before HM. This strategy is expected to minimize packet loss and high latency during handover.

**Reactive Handover**

Due to small FAP’s coverage, its lower power and the density of FAPs, the MS in femtocell system will facing the very frequent and unnecessary handover since the MS will move from one femtocell to other femtocell repeatedly. To mitigate the overhead of handover, the reactive handover scenario is applied. Reactive handover tends to postpone the handover as long as possible, even though it has discovered the new RSSI signal. The handover is triggered only when the MS (almost) lose its serving BS/FAP signal.

### 3.4 Spectrum issues

**3.4.1 Spectrum usage (shared, non-shared)**

Table 8 presents different strategies for allocating spectrum resources to femto and macro layers, along with their main advantages and drawbacks in terms of spectrum efficiency and interference management.

**3.4.2 Orthogonal vs. Co-channel allocation for FAP and BS**

In OFDMA systems, different subsets of subchannels are assigned to individual users, thus allowing two main strategies for subchannel allocation in the two-layer macro and femto network: orthogonal or co-channel allocation. The main issues on each alternative are shown in Table 9.

### 3.5 Access methods

One of the main challenges of the femtocell technology is how to allocate spectrum between macro and femtocell, or “second tier”, systems. Two main approaches are possible: spectrum splitting or spectrum sharing ([HAD01]). Spectrum sharing, on its turn, may be full or partial.

In spectrum splitting, macro and femtocells are given orthogonal frequency bands. This approach is the simplest one, from the interference point of view, as no cross-tier interference is expected. In such a case, macrocell and femtocell tiers can be considered as totally separated networks. However, this solution is not always possible, as operators do not own additional spectrum to allocate to femto users, rather than mobile users. Furthermore, a rigid spectrum splitting is not an efficient solution, as splitting the spectrum into smaller sub-bands implies a lower throughput to macrocell users, which is clearly not desirable.
<table>
<thead>
<tr>
<th>Principles</th>
<th>Dedicated channel</th>
<th>Co-channel</th>
<th>Partial co-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The femto and macro layers are each assigned to specific spectrum resources (i.e. one specific channel in UTRA systems).</td>
<td>The same spectrum resources are shared by both femto and macro layers.</td>
<td>The macro layer uses all available spectrum resources, whereas the femto layer only uses a subset – the shared part (i.e. in UTRA systems, one specific channel is used by the femto and macro layers, while a second channel is exclusively used by the macro layer).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interests</th>
<th>Dedicated channel</th>
<th>Co-channel</th>
<th>Partial co-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This approach is optimal for reduction of the cross-layer interferences (i.e. interferences between femto communications and macro communications). Maximum power can be used at the femto base station, then femto coverage is optimal (provided that interference with a neighbour femtocell does not occur). Usual radio planning rules can still be employed for the macro layer simulation.</td>
<td>This approach is optimal in terms of spectrum efficiency as the spectrum resources can be efficiently distributed over the whole network users. Feasibility has been proved for open access.</td>
<td>The macro layer can take profit of all available spectrum resources, while the macro user can switch to the non-shared part of the spectrum when interference occurs with the femto layer.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Drawbacks / limitations</th>
<th>Dedicated channel</th>
<th>Co-channel</th>
<th>Partial co-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This approach is not optimal in terms of spectrum efficiency, as the spectrum resource is divided in two independent parts for each layer of the network. This approach does not prevent from interferences between neighbour femtocells. This approach requires 3G operators to have bought licenses for two different channels.</td>
<td>Sophisticated techniques are required to mitigate cross- and co-layer interferences in case of closed access.</td>
<td>This approach does not prevent from interferences between neighbour femtocells. This approach requires 3G operators to have bought licenses for two different channels.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Key issues</th>
<th>Dedicated channel</th>
<th>Co-channel</th>
<th>Partial co-channel</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Resource allocation must be efficiently controlled to mitigate interferences, based either on self-optimisation and cooperation solutions. New radio-planning rules have to be elaborated to account for the impact of the random femto-layer deployment on the macro performance.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Spectrum usage
Orthogonal subchannel allocation | Co-channel allocation
--- | ---
**Principles** | The licensed spectrum is divided in two orthogonal parts: one fraction of subchannels assigned to the macro layer, and the other fraction assigned to the femto layer. | Subchannels of the whole licensed spectrum may be allocated to femto and macro communications.

**Interests** | This approach is optimal for reduction of the cross-layer interferences (i.e. interferences between femto communications and macro communications). | This approach is optimal in terms of spectrum efficiency as the spectrum resources can be efficiently distributed over the whole network users.

**Drawbacks / limitations** | This approach is not optimal in terms of spectrum efficiency, as the spectrum resource is divided in two independent parts for each layer of the network. This approach does not prevent from interferences between neighbour femtocells. | Sophisticated techniques are required to mitigate cross- and co-layer interferences.

**Key issues** | Fractions of subchannels must be carefully dimensioned to be adapted to the traffic distribution into each layer of the network. | Sub-channel allocation must be efficiently controlled to mitigate interferences, based either on self-optimisation and cooperation solutions. New radio-planning rules have to be elaborated to account for the impact of the random femto-layer deployment on the macro performance.

Table 9: Orthogonal vs co-channel allocation in OFDMA systems

Conversely, in the spectrum sharing case, the same spectrum is used by both macro and femtocells. This approach reaches a higher spectral efficiency because both tiers access, potentially, all resources. Nevertheless, in such a configuration, cross-tier interference occurs, which could degrade the overall network performance, unless interference is efficiently handled. An intermediate solution entails partial spectrum sharing, where the macrocell system uses the whole available bandwidth, whereas the femtocell uses only a fraction of such a bandwidth. An efficient use of such a scheme would be achieved by endowing the FAP with the capability of adapting the spectrum to the least occupied spectrum regions.

Assuming a spectrum-sharing approach, the two main aspects of FAPs, which must be taken into account for the interference issue, are:

- Co-channel spectrum sharing between femtocells and macrocells;
- “Random” location of FAPs.

Typically, FAPs are installed by end-users in a “plug-and-play” manner, which translates into “randomness” in their locations: they can be deployed anywhere inside the macrocell area. For these two reasons, interference in two-tier networks is quite different than in conventional cellular networks, and endangers their successful co-existence. A typical scenario is the “Dead Zone” or “Loud Neighbour” problem (see Figure 34. Two different scenarios for the "dead zone" problem [CHAN01] ), where mobile users transmit signals to the macrocell BS, from positions near FAPs but far from the macrocell BSs, causing significant macro-to-femto interference in the uplink.

In the downlink, these users likewise suffer from low signal to interference ratio (SIR) because of the strong interference from the FAPs. These effects are similar to the well known near-far problem, but exacerbated by the de-centralization and lack of coordinated power control inherent in a two-tier network. Because of the presently non-existent coordination between FAPs and macrocell BSs, decentralized strategies for interference management such as access control are needed (as suggested in [XIA01]).
Access control mechanisms play an important role in mitigating cross-tier interference and handover attempts, which is why they have to be carefully chosen depending on the customer profile and the scenario under consideration.

The 3GPP LTE and WiMAX standards have created a set of detailed requirements for femtocell access methods. In both cases three main different strategies access have been proposed so far (see Figure 35. Access methods [DLROCHE01]):

- **Open access**: All users are allowed to connect to the FAP;
- **Closed access**: Only a subset of users, defined by the femtocell owner, can connect to the femtocell. This model is referred to as closed subscriber group (CSG) by the Third Generation Partnership Project (3GPP);
- **Hybrid access**: Non-subscribers use only a limited amount of the femtocell resources.

Since there are three access modes for femtocells, it is not possible for UE to identify the type of femtocell based only on the fact that the cell broadcasts a CSG identity because hybrid femtocells would also broadcast a CSG identity. In order to differentiate the three access modes, 3GPP has defined a CSG indicator which is a Boolean flag identifying whether a cell is open or closed. Table 10 summarizes how a femtocell can be identified as closed, open, or hybrid based on the CSG indicator and the presence/absence of the CSG identity in the broadcast system information of the cell ([GOLAUP01]).

<table>
<thead>
<tr>
<th>Access Mode</th>
<th>CSG Indicator</th>
<th>CSG ID (absent/present in system information)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed</td>
<td>TRUE</td>
<td>Present</td>
</tr>
<tr>
<td>Open</td>
<td>FALSE</td>
<td>Absent</td>
</tr>
<tr>
<td>Hybrid</td>
<td>FALSE</td>
<td>Present</td>
</tr>
</tbody>
</table>

Table 10. Identification for closed, open and hybrid access mode for LTE femtocells
As far as performance is concerned, it has been shown in [DLROCHE01] that open access improves the overall capacity of the network, mainly because macrocell users can connect to nearby femtocells in locations where the macrocell coverage is deficient. From an interference viewpoint, this avoids femtocells behaving as interferers since outdoor users can also connect to indoor femtocells. As a drawback, open access will increase the number of handoffs and signaling. Furthermore with this type of access, security issues apply. Moreover, recent customer surveys show that open access is commercially challenging for operators. This is because femtocells are paid by subscribers, who are not keen to accept non-subscribers as users of their own femtocells, unless they obtain some kind of benefit/revenue. Closed access femtocells are thus more likely to be deployed in the home environment. However, this implies that power leaks through windows and doors will be sensed as interference by nearby passing macrocell users, thus decreasing their signal quality.

Hybrid access methods reach a compromise between the impact on the performance of subscribers and the level of access granted to nonsubscribers. Therefore, the sharing of femtocell resources between subscribers and nonsubscribers needs to be finely tuned. Otherwise, subscribers might feel that they are paying for a service that is to be exploited by others. The impact on subscribers must thus be minimized in terms of performance or via economic advantages. In the following sections, specific examples of OFDMA-hybrid access methods for several technologies will be described. It is useful to remind that the 3GPP standardization body proposes an asymmetric transmission scheme for uplink (UL) and downlink (DL). The downlink in 3GPP-LTE is based on an OFDMA transmission scheme. This choice, which is considered power inefficient, is tolerable since in the case of DL transmission the power amplifier is placed at the base station (e-Node-B in 3GPP terminology). In the base-station, power is available and the extra complexity is shared over many mobile terminals. On the other hand, most of the mobile terminals are battery powered, and constrained to be of low cost to enable a massive deployment. Hence, 3GPP specifications suggest for the 3GPP-LTE UL signal a reduced peak-to-average–power-ratio (PAPR) transmission scheme called single-carrier frequency-division multiple-access (SC-FDMA). This eases the mobile terminal task of maintaining highly efficient signal transmission by its power amplifier.

### 3.5.1 Open FAP access

In open FAP access, all users (subscribers and nonsubscribers) are allowed to connect. There is thus no distinction between these two groups, and they are just referred to here as users. The use of open FAPs at home would reduce the interference problems caused by CSG FAPs. Indeed, all passing users would be authorized to connect to any femtocell, thus reducing the negative impact of the femtocell tier on the macrocell network. In this case the users are always connected to the strongest server (either macro or femto), avoiding cross-tier interference. As a result, the overall throughput of the network increases ([DLROCHE01]).

Furthermore, open access FAPs allow different types of deployments. Inside homes, this type of FAP will be deployed in random locations, *self-organization* being a good solution to minimize the negative impact of femtocells on other cells. On the other hand, when deployments are done by an operator, interference can be mitigated throughout network planning and optimization. The location, power, and frequencies assigned to each femtocell can in this case be planned in advance.
Nevertheless, open access has some drawbacks as well. It reduces the performance for the femtocell owner due to the sharing of the femtocell resources with nonsubscribers. Moreover, open access substantially increases the amount of handovers between cells due to the movement of outdoor users. A user moving in a residential area will hand over from one femtocell to another or to the umbrella macrocell. This will have a negative impact on the operator because the signaling in the network increases as well as the probability of the call being dropped due to failure in the handover process. On the other hand, open access combined with high quality DSL link allows the use of macrodiversity (including distributed beamforming) and hence the potential of increasing the capacity at cell edges.

Furthermore, the chances for handover failure increase if the femtocell neighbour list is not properly configured and updated. Regardless of this, different solutions have been proposed in which a centric sensing of the radio channel is used as a means to obtain parameters about the surrounding environment and update the femtocell neighbour list. Moreover, current base stations store only a few neighbour relationships in such a list. However, this number will be insufficient in large open access femtocell deployments, where the relationships between femtocells (more likely to be turned on and off) must be handled in a different way than between macrocells and femtocells. Hence, before open FAPs are widely deployed, research is required in order to support new algorithms to handle more neighbours and their different natures in a fast manner.

Additionally, in a massive deployment of FAP, the number of cell ID might prove insufficient (currently limited to 512 in UMTS) in the coverage area of a macrocell. New ways to allocate distributedly ID that avoids collision and confusion are required.

### 3.5.2 Closed FAP access

In scenarios with CSG FAPs, nonsubscribers are not allowed to connect to the network through a femtocell, even if its signal is stronger than that of the closest macrocell. Therefore, strong Cross-tier interference exists between both tiers; for example, femtocells could jam the downlink communication of nearby passing nonsubscribers connected to a far macrocell, and nonsubscribers located close to a femtocell could jam the femtocell uplink. One of the most challenging cases of cross-tier interference in CSG FAPs, in both downlink and uplink, occurs when a nonsubscriber enters a house hosting a CSG femtocell. In this case the interference power is much larger than that of the carrier signal. To avoid this worst case scenario, the femtocell owner should authorize guest nonsubscribers in a fast manner so that they gain access to the femtocell. However, the list of authorized users is controlled by the operator, resides in the core network, and has to be manually updated by the femtocell owner.

Co-tier interference also arises between neighbouring femtocells in dense deployments. In many cases users will install their FAP’s at random positions within their homes (e.g., close to the room of a neighbour or close to a window). In this case, subscribers will sometimes be severely jammed by neighbouring femtocells, and thus unable to connect. Therefore, solutions are required to reduce both cross-tier and co-tier interference, allowing the deployment of a large number of femtocells within the existing networks. Interference cancellation and avoidance techniques for femtocell networks are hence currently an important research topic. In order to guarantee femtocell connectivity and mitigate interference, the power radiated by the FAP must be tuned to ensure sufficient coverage to femtocell subscribers and minimize leakage of power outside the premises. This can be done by self-optimizing the femtocell radiated power so that each femtocell sets its power to a value that on average is equal to the received signal strength from the closest macrocell in a target femtocell radius.

Another solution to mitigate the interference problem is the use of sector antennas in the FAPs, in order to minimize the overlapping of coverage areas. Furthermore, the use of several radiating elements to perform beamforming and adapting the coverage area of the femtocell to the shape of the household have also been suggested.
3.5.3 Hybrid FAP access

Hybrid access methods reach a compromise between the impact on the performance of subscribers and the level of access granted to nonsubscribers. Therefore, the sharing of femtocell resources between subscribers and nonsubscribers needs to be finely tuned. Otherwise, subscribers might feel that they are paying for a service that is to be exploited by others. The impact on subscribers must thus be minimized in terms of performance or via economic advantages (e.g., reduced costs). In this section the particular case of OFDMA hybrid access method is depicted. OFDMA systems offer two degrees of freedom for the purpose of resource allocation (frequency and time), hence providing higher flexibility in the management of the resources nonsubscribers can use. Furthermore, since OFDMA resources (time slots and frequency subcarriers) are orthogonal, interference can also be better controlled in the neighbourhood of the femtocell. As for the open access case, macrodiversity techniques can also be used.

Thus, users unable to connect to the macrocell because of lack of coverage or interference could still use a fraction of the femtocell resources. The hybrid access method in OFDMA femtocell networks consists of managing the sharing of the OFDMA resources (frequency and time) between subscribers and nonsubscribers. Therefore and first of all, these resources have to be defined. In OFDMA systems subchannels contain a series of subcarriers, which can be adjacent or pseudo randomly distributed across the spectrum in order to exploit either multi-user or frequency diversity (the choice of either one or the other channelization mode depends on the accuracy of the channel state information: in static environments with stationary interference, the former is preferred).

A nonsubscriber allowed access to a given subchannel can use it, for instance, during the whole transmission frame. However, if the network operator owns only a little bandwidth for its femtocells, one subchannel might seem a large resource to be shared. In such situations it is necessary to increase the granularity of the resource allocation, subdividing subchannels over the time domain (OFDM symbols). In general, it can be said that the smaller the resource, the better the approximation to the solicited throughput of a nonsubscriber. Time sharing of the channel implies the definition of scheduling strategies that give preferential channel access to subscriber users. This may be achieved by limiting the allowed levels of QoS for nonsubscribers.

3.6 Services

Femtocells were introduced basically as a coverage improvement to help users to combat signal fading, especially if they were located indoor (e.g. in house/apartment room or office building). Femtocells Access Points were placed inside apartment rooms and office cubicles so that users can access the network through those FAPs instead of macro radio stations (i.e. macro BTS, Node B, eNodeB or WiMAX BS).

The service offered by femtocells is voice service, mobile application and data. The femtocells help to improve the voice indoor coverage, that will guarantee the good quality of voice call where ever a users in located inside an indoor site. As voice coverage improved, the data services will also gain more coverage and capacity. Those services are firstly driven by the poor quality of signals which cause poor quality for voice calls and data connections. There may be specific subscription plans offered to the user to attract femtocell usage.

Based on the general user characteristic proposed by Femto-forum [FEM10], the services can be described as follow:

3.6.1 Family Services

Services offered for the family are mainly voice and data services. For voice services, type of services can vary from regular voice calls, high quality voice calls, or special charging for indoor voice calls. For the data services, type of services will mainly be dominated by internet access. Users can enjoy high quality internet access using their smart phones anywhere inside their premises. Other data services that can be offered are SMS, video calls and home automation. From the user’s point of view, there will be nothing to do to enjoy the services.
3.6.2  Personal Services

Services offered for the personal are mainly data services, which is heavy internet access. Femtocells may offer managed internet access not only inside the user house or apartment but also in public places with public FAPs.

3.6.3  Business Services

Similar with Family Services, Business users can have high quality voice and data services. More advanced than Family Services, other advanced communications and business applications can be added on top of both voice and data services to meet business user specific requirements.

Other future advanced services that can be offered according to [LUENING09] can be categorized as follow:

- Services: Virtual home number, SMS alerts, music/video synchronization, home automation
- The Box: femto+Wifi, Fixed line RJ-11 ports, router ports (fully replacing your DSL router and home phone jack)
- Integration: a feature addition to set-top boxes or integrated with a DSL modem (fully replacing the DSL modem)
- Public Access: femtocells may begin to proliferate in coffee shops, malls, and other hot spots
- Corporate: femtocells may begin to proliferate in corporate offices, ensuring employees and visitors full access to high quality voice and to fast mobile data.

3.7  Backhaul link

Several backhaul technologies will be used for connecting femtocells to cellular network:

- Mostly residential user oriented:
  - xDSL,
  - FTTH,
  - Cable,
- Mostly enterprise user oriented:
  - Leased telecommunication line,
  - satellite connection (e.g. VSAT technology),
  - Fixed WiMAX,
  - Digital radiolinks,
  - xDSL also for enterprise

A special case of backhaul should also be considered for inter-connecting of femtocells in the sites where they are deployed. In case of residential users with large homes, Power Line Communication maybe used as an alternative to Ethernet cable solutions. In the enterprise context, the Intranet will play this role.

Coming back to the main backhaul concept, several business models apply depending on the relationship between the cellular network operator and the backhaul link operator:

- Single entity operating both cellular network and backhaul link.
• Different entities operating cellular network and backhaul link, with agreement between them,
• Different entities operating cellular network and backhaul link, with no agreement between them,

The QoS enforcement of the backhaul link will rely on which of the above model is considered. As an example in the last case there might be no possibility to provide any differentiated QoS characteristics for the femtocell related traffic.

The QoS requirement of the backhaul link will also be determined according which advanced architecture is considered, which in turn will determine which content will be carried on the backhaul link.

Baseline architecture:
If the baseline architecture is considered, then the traffic on the backhaul will be mapped to user services as they described in section 3.6.

If plain telephony is the main service in use through the femtocell, then femtocell related traffic will represent only a small part of the backhaul capacity.

On the other hand if the full range of services is expected to be used, then femtocell related traffic may represent a significant share of the backhaul link capacity, and QoS issues may arise.

Limited cooperation among macro and femtocells:
If some kind of cooperation is achieved between femtocells and macrocells, then additional type of content will be carried over the backhaul links, which will be made of all control signalling required for such cooperation. Of course if cooperation is limited to intra femtocell cooperation, the main backhaul toward the cellular operator core network may not be involved.

Full cooperation among macro and femtocells:
Full cooperation between macrocells and femtocells will involve active sets of cells (possibly including both macrocells and femtocells) serving one terminal.

As far as the downlink is involved, full cooperation may not significantly impact xDSL connections, because anchor points for the active set will be located in the cellular network core network.

However, cooperation may also be considered for the uplink direction. Then, for a given terminal, a single decoding entity should receive all analogic signals (or at least quantized soft bits) received from an active set of cells. This kind of solution will impact backhaul traffic and will be analysed carefully in this respect.

3.7.1 QoS of backhaul link
As seen in the previous section, the requirements in terms of QoS for the backhaul link will depend on several factors:

• which agreement there is between backhaul link operator and cellular network operator,
• which user services are proposed and which associated QoS level should be granted to users,
• which transport technology is used for backhaul.

As far as user services are concerned, those that require QoS enforcement should first be sorted out. Typically, plain internet services are based on best effort policy and should not be considered for designing a QoS architecture for femtocells. In practice, QoS guarantees may be needed in case of telephony application (including video telephony) and more generally in case of IMS applications.

Ideally QoS should be enforced “end to end” from the femtocell to the cellular core network gateway. In practice, QoS enforcement may be enforced at IP level in the routers, using e.g. IntServ or DiffServ protocols, and also at level II when referring to access technologies such as xDSL, FTTH, WiMAX,
etc. To insure consistency along the full path, mapping functionalities should be considered for mapping IP QoS classes of services to level II QoS requirements.

As an example of the use of QoS over xDSL, some Internet Service Providers use ATM Virtual Containers with differentiated QoS guarantees, when providing VoIP services to their customers.

Such heterogeneous mechanisms maybe coordinated from the cellular network through the IMS Policy Decision Function in order to provide end to end QoS.

It should be noted however, that because VoIP services consume very little bit-rate when compared e.g. to xDSL bandwidth, even best effort VoIP services on xDSL links are known to provide good user experience.

Therefore the “best effort simplification” for the path going from the femtocell to the cellular core network gateway is also a good practical deployment solution, at least now.

This simplification doesn’t exclude agreement between cellular operator and Internet Service Provider. As an example a certification process can be proposed by the cellular operator in order to identify which Internet Service Provider provides characteristics in accordance with the deployment of femtocells. This certification process gives guarantees about the quality of Internet access as a whole, without any attempt to give specific QoS level to femtocell traffic within the Internet traffic.

### 3.8 Configuration methods

A customer purchased a FAP from local electronic store that has been pre-configured to work in macro network operators. The FAP should not require radio planning. Since operators do not know a priori where any individual FAP will be deployed, they cannot reconfigure their macro network to account for this. Macro network operators do not need to negotiate with landlords for site acquisition. Instead, they need to make a compelling and attractive commercial offer to their customers who will host it themselves.

However, in the early deployment of Femto, it may be the case that the operator will monitor the equipment installation, inside user’s home, for regulatory issues or simply to keep control of the network. This is for instance the case in Japan for NTT Docomo current deployment of 3G femto cells.

Self-configurable FAP are however of simpler use for both users and operator.

Self-configuring FAP does not require any specific parameters to be preconfigured or downloaded. The FAP should directly connect to its femtocell Gateway and receive specific configuration information automatically without human intervention.

The FAP is able to self-discover and further monitor the wireless environment, and self-configure the RF parameters, under the macro network operator control, in such a way that the interference to neighboring macro BS or FAP is minimized without any parameter setting.

Use case description:

- FAP and femtocell Gateway perform authentication and authorization procedures. After FAP is authenticated and authorized to provide femto services, a backhaul connection is created between FAP and femtocell Gateway at service provider network. Since the connection for authentication and authorization needs to be established through public Internet, the connection may need to be secured.

- The FAP performs self-discovery to detect the PHY / RF parameters of the surrounding macro BS and other FAP.

- FAP reports the PHY / RF parameters of neighbouring macro BS / FAP to the SON function that process them.
- SON function will select a set of PHY / RF parameters for FAP to use, based on the analysis of the PHY / RF parameters being reported by FAP.
- Other processes may be required such as location determination and network synchronization.
- Indicators on the FAPs are likely to be required to show:
  - Broadband signal connection active and online
  - Connection into the operator’s network active and online
  - If UE is camped on the FAP
  - When a voice or data call is active

A straightforward installation should simply involve connecting the box to the broadband DSL line and power. If there is a GPS function equipped in FAP, then FAP needs to be located near a window. The GPS information is used to get spectrum license permits.

It should be noted from the scenarios’ analysis that 3GPP has provided more detailed study of scenarios covering both interference and mobility management than other development bodies such as Femto Forum. The scenarios proposed by Femto Forum discusses mainly the interference scenarios and are mainly based on the works done by 3GPP.
4 REQUIREMENTS

Based on the scenarios described in the previous sections, this section summarizes the requirements related to femto access points, and to some extent the requirements related to other components that are used in conjunction with femtocells, such as user devices as well as core network.

4.1 System requirements

System level requirements adopted in FREEDOM for the FAP deployment are listed below:

- The FAP should be designed in such a way that it will be compatible with (macro layer) wireless system.
- The FAP should be able to be connected to an IP backhaul network (DSL, cable or Fiber) on the one hand and provide standard wireless operation on the other hand.
- The FAP should be able to be uniquely identified (manufacturer, software version, user to which it is attached to). In addition, the FAP should provide a mean to determine whether the equipment is a FAP or a macro BS.
- The FAP should be remotely manageable by the mobile operator.
- The FAP system should be able to operate in various access methods including closed access, open access and hybrid access. In that context, it should be able to list authorized users and to add/remove such users.
- The FAP from a given operator should allow access (assuming open access) to users from different operators, assuming that a roaming agreement among those operators has been settled.
- The FAP system should be able to support a theoretical unlimited number of FAPs to support very dense deployment. However in practice there will be limitation in the number of FAP deployed due to interference as well as processor limitation of FAP gateway or network management system.
- The FAP system should meet same performance level as the one of the macro system, with the noticeable exception that FAP system does not have to support high speed mobility. Moreover, latency requirement may be less controllable compared to macro network to take into account IP backhaul connection.
- The FAP system should support mobility and specifically handover between macro BS and FAP layers (and reversely) as well as FAP to FAP handover.
- The FAP system should support deployment without predetermined planning. Similarly the FAP system should be able to support the introduction/leave of new FAPs.
- The FAP system should support emergency services.
- The FAP should be able to support up to 10 simultaneous users.

4.2 Radio requirements

The radio requirements adopted in FREEDOM for the FAP deployment are listed below:

- The FAP should support user terminal within a typical range of 30m – 10cm. The dynamic range of the FAP should therefore be able to support very close terminal (which may transmit at full power if no efficient power control is enabled).
- The FAP transmit power should be typically less than 10mW
The FAP should be able to operate in an environment with close WiFi or Bluetooth system. Coexistence with these wireless technologies should be ensured. Moreover, the FAP system may be able to support seamless handover with WiFi.

The FAP system should minimize the interference it may cause to the macro layer, as well as interference between multiple FAPs.

The FAP should provide measurements means to be able to identify and assess interference that may arise from the neighbouring FAPs (or macro BS).

The FAP should be able to adjust its transmission parameters especially maximum possible transmit power as well adjust its current transmit power.

The FAP should include interference mitigation techniques in order to protect control channel as well as maximize spectral efficiency.

The FAP should include enough antennas to provide advanced MIMO schemes as defined by the wireless standard.

The FAP should be agile enough to support various ranges of bandwidth and of carrier frequency. However due to Hardware and Software limitation some FAP may be able to only support limited ranges of bandwidth and frequency.

The FAP should be able to operate without GPS synchronisation (as in home coverage of GPS is rather poor. The clocking information for synchronization may be traversed over IP network (i.e IEEE 1588).

4.3 Security requirements

Security issues assumptions adopted in FREEDOM are:

The FAP should be able to establish an encrypted communication between itself and the core network of the mobile operator. This encryption should be controlled by the management system.

The FAP should be able to authenticate itself prior to any connection to the mobile operator network. The FAP should be able to authenticate the core network it is connected to. For that purpose the FAP may need to be pre-configured by the operator prior to be released to the end user.

The FAP should ensure data integrity and protection when bridging the user communication from the air interface and the communication with the core network, through the IP broadband backhaul.

The FAP system should have means to verify that any software installed or to be installed on the FAP is valid, signed and approved by the operator. The FAP system should have means to protect the installed software to be hacked especially in the spirit of entering the mobile operator network.

The FAP should have means to limit the possibility to be moved from one home to the other without informing or agreement from the operator. The FAP should be able to identify its current location and send the information to the FAP Gateway.

The FAP should include all the radio resource management strategies to be able to offer various QoS profiles as defined by the wireless standard considered.

4.4 Management and Self-management requirements

The system management requirements adopted in FREEDOM are:

The FAP should be remotely manageable by the network regular O&M system, using for instance TR-069 or DOCSIS or other standard for remote management.
• The FAP should be able to enable/disable radio operation based on network operator guidance.
• The FAP should be able to be installed without the need of a human specialist.
• The FAP should be able to adapt autonomously to changes in its environment (change in radio condition, change in traffic load). In particular, the FAP should be able to adapt its power consumption to its actual usage.
• The FAP should be able to autonomously discover its RF environment. It should autonomously adapt radio resource management to minimize interference.

4.5 Backhaul and Core network requirements
In theory, the core network does not have to support specific requirements when used in conjunction of femtocells.
However, the operator core network should be scalable enough to support in theory millions of FAPs.
The IP backhaul used to connect FAP to operator core network should be of enough quality to be qualified as “carrier grade”. Moreover, to enable smart radio resource management (collaboration between FAPs or between FAP and macro), real broadband connectivity should be required.

4.6 End-user equipment requirements
The FAP system should be transparent for the end-user device.
However, depending on the femtocell model (close or open group), the end-user equipment may not be allowed to attach to every FAPs. Thus, the end-user equipment may have to adapt measurements reports to reports only FAP it is allowed to attach to.
Due to the vicinity of FAP, the end-user equipment may have to put in place stronger power control mechanisms, especially when the distance between FAP and user equipment is limited.
5 SIMULATION METHODOLOGY

The simulation methodology used in FREEDOM (precisely in WP3, WP4 and WP5) is mainly based on the 3GPP simulation model given in

- Annex A of [3GPP-TR25.814], for reference system deployment, channel models, traffic models, system performance metrics, reference UE and Node-B, scheduling and resource allocation, multiantenna subsystems, system configuration and performance, cell and user throughput evaluation, E-UTRA PHY-layer (UL and DL)

- Annex A of [3GPP-TR36.814], for reference system deployments, traffic models, system performance metrics, antenna gain, effective IoT, system level simulation calibration.

It has to be remarked that FREEDOM will consider for the simulation methodology for the channel models already included in [3GPP-TR25.814] as starting guidelines to be complemented by specific channel models (ITI, ITO, OTI) will be assessed and included in FREEDOM, mainly coming from the WP3A1.

The simulation methodology discussed further regards following aspects:

- Wireless system (3GPP LTE-A or IEEE 802.16m) characteristics;
- Path loss models;
- Channel models;
- Spectrum usage;
- Traffic models;
- Interference power models;
- Backhaul quality models;
- Synchronisation error models;
- PHY-layer abstraction;
- Mobility and handover;
- System performance metrics.

5.1 Key system descriptors

LTE-A [3GPP-TR.36.814] introduces the terminology presented in Table 11 for the new nodes considered in the network.

<table>
<thead>
<tr>
<th>Backhaul</th>
<th>Access</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remote Radio Head (RRH) cells</td>
<td>Several μs latency to macro network or cell</td>
<td>Open-access</td>
</tr>
<tr>
<td>Hotzone cells</td>
<td>X2</td>
<td>Open-access</td>
</tr>
<tr>
<td>Femto cells</td>
<td>For Further Study (FFS)</td>
<td>Closed Subscriber Group (CSG)</td>
</tr>
<tr>
<td>Relay nodes</td>
<td>Through air-interface with a macro-cell (for in-band RN case)</td>
<td>Open-access</td>
</tr>
</tbody>
</table>

Table 11. Categorization of new nodes [3GPP-TR36.814].

Notice that in general the femtocell terminal (FAP) is placed indoor, working in a closed-subscriber group (CSG) and so far it has not been defined the type of backhaul. This latest aspect has been
defined for the hotzone cells by using the X2 interface. The hotzone cells are envisioned for outdoor scenario and operating in open-access mode.

Table 12 through Table 19 show a list of values of the different parameters about the system, macro-BS, FAP and UE to be considered by the simulations. We introduce the values commonly assumed by the LTE-A and 802.16m, but we specify the ones selected by the FREEDOM project. Some are obtained from [FEM-OFDMA10].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Common assumptions (based on standard LTE-A)</th>
<th>Preferred FREEDOM selection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carrier Frequency</strong></td>
<td>2.0 / 2.6 GHz</td>
<td>2.0 GHz</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>3GPP case1 and case3): TDD: 1.4, 3, 5, 10, 15 and 20 MHz, FDD: 10+10 MHz 3GPP case1 extended): TDD: 80 MHz, FDD: 80+40 MHz</td>
<td>TDD: 20 MHz FDD: 10+10 MHz</td>
</tr>
<tr>
<td><strong>Noise level</strong></td>
<td>-174 dBm/Hz</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td><strong>Downlink modulation/access</strong></td>
<td>OFDMA</td>
<td>OFDMA</td>
</tr>
<tr>
<td><strong>Uplink modulation/access</strong></td>
<td>SC-FDMA</td>
<td>SC-FDMA</td>
</tr>
<tr>
<td><strong>Frame duration</strong></td>
<td>10 ms</td>
<td>10 ms</td>
</tr>
<tr>
<td><strong>Number of slots per frame</strong></td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Subframe definition</strong></td>
<td>2 adjacent slots</td>
<td>2 adjacent slots</td>
</tr>
<tr>
<td><strong>Number of OFDM symbols per slot</strong></td>
<td>6 (for long cyclic prefix) or 7 (for short cyclic prefix)</td>
<td>7</td>
</tr>
<tr>
<td><strong>Subcarrier spacing</strong></td>
<td>Fixed to 15 KHz</td>
<td>Fixed to 15 KHz</td>
</tr>
<tr>
<td><strong>Resource block</strong></td>
<td>6 or 7 symbols × 12 subcarriers. Allocated in pairs in time domain</td>
<td>6 or 7 symbols × 12 subcarriers. Allocated in pairs in time domain</td>
</tr>
<tr>
<td><strong>Sync broadcast channel</strong></td>
<td>6 RB at subframes 0 and 5 of each frame</td>
<td>6 RB at subframes 0 and 5 of each frame</td>
</tr>
<tr>
<td><strong>DL control (MBS)</strong></td>
<td>3 OFDM symbols in each subframe</td>
<td>2 OFDM symbols in each subframe</td>
</tr>
<tr>
<td><strong>DL control (FAP)</strong></td>
<td>1 OFDM symbols in each subframe</td>
<td>1 OFDM symbols in each subframe</td>
</tr>
<tr>
<td><strong>Reference signal (DL)</strong></td>
<td>1 transmit antenna: 8 resource element per subframe 2 transmit antennas: 16 resource element subcarrier per subframe 4 transmit antennas: 24 resource element per subframe</td>
<td>1 transmit antenna: 8 resource element per subframe 2 transmit antennas: 16 resource element subcarrier per subframe 4 transmit antennas: 24 resource element per subframe</td>
</tr>
<tr>
<td><strong>Reference signal (UL)</strong></td>
<td>12 subcarriers per RB</td>
<td>12 subcarriers per RB</td>
</tr>
<tr>
<td><strong>Cyclic prefix to symbol duration ratio</strong></td>
<td>4.69, 16.47 or 33.33 µs</td>
<td>4.69 µs (7.03%)</td>
</tr>
<tr>
<td><strong>Total PHY overhead (SISO)</strong></td>
<td>Variable, depending on bandwidth, UL/DL resource allocation, TDD/FDD mode and system configuration</td>
<td>FDD-DL: 19% (2 control symb.), 29% (1 control symb.), FDD-UL: 17%; TDD: 26 – 38% depending on configuration (check [Becvar2010])</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Supported modulation in DL</strong></td>
<td>QPSK, 16 QAM, 64 QAM</td>
<td>QPSK, 16 QAM, 64 QAM</td>
</tr>
<tr>
<td><strong>Supported modulation in UL</strong></td>
<td>BPSK, QPSK, 8PSK, 16QAM</td>
<td>BPSK, QPSK, 8PSK, 16QAM</td>
</tr>
<tr>
<td><strong>Maximum block size</strong></td>
<td>6144 bits</td>
<td>6144 bits</td>
</tr>
<tr>
<td><strong>Spatial multiplexing</strong></td>
<td>Single layer for UL per UE Up to 4 layers for DL per UE MU-MIMO supported for UL and DL</td>
<td>Single layer for UL per UE Up to 4 layers for DL per UE MU-MIMO supported for UL and DL</td>
</tr>
</tbody>
</table>

Table 12. LTE-A parameters.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Common assumptions in standards (LTE-A and 802.16m)</th>
<th>Preferred FREEDOM selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total BS transmit power</td>
<td>43 dBm – for BW of 1.25 MHz and 5 MHz, 46/49 dBm – for BW of 10 MHz and 20 MHz. Some evaluations to exploit carrier aggregation techniques may use wider bandwidths e.g. 60 MHz or 80 MHz (FDD). For these evaluations [49 dBm] Total BS transmit power should be used.</td>
<td>46 dBm</td>
</tr>
<tr>
<td>BS antenna height</td>
<td>32 m</td>
<td>32 m</td>
</tr>
<tr>
<td>Antenna pattern (horizontal)</td>
<td>$A_{H}(\varphi) = \min \left[ 12 \left( \frac{\varphi}{\varphi_{3db}} \right)^2, A_m \right]$</td>
<td>$A_{H}(\varphi) = \min \left[ 12 \left( \frac{\varphi}{\varphi_{3db}} \right)^2, A_m \right]$</td>
</tr>
<tr>
<td>For 3-sector cell sites with fixed antenna patterns</td>
<td>$\varphi_{3db} = 70^\circ, A_m = 25$ dB</td>
<td>$\varphi_{3db} = 70^\circ, A_m = 25$ dB</td>
</tr>
<tr>
<td>Antenna pattern (vertical)</td>
<td>$A_{T}(\theta) = \min \left[ 12 \left( \frac{\theta - \theta_{tilt}}{\theta_{3db}} \right)^2, SLA \right]$</td>
<td>The same if it is needed</td>
</tr>
<tr>
<td>For 3-sector cell sites with fixed antenna patterns</td>
<td>$\theta_{3db} = 10, SLA_T = 20$ dB</td>
<td>The same if it is needed</td>
</tr>
<tr>
<td>Combining method in 3D antenna pattern</td>
<td>$A(\varphi, \theta) = \min \left( -\left( A_{H}(\varphi) + A_{T}(\theta) \right), A_e \right)$</td>
<td>The same if it is needed</td>
</tr>
<tr>
<td>Antenna orientation</td>
<td></td>
<td>The same if it is needed</td>
</tr>
<tr>
<td>Number of sectors</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Number of antennas at BS</td>
<td>2 or 4</td>
<td>4</td>
</tr>
<tr>
<td>Antenna spacing</td>
<td>$4 \times \lambda$</td>
<td>$4 \times \lambda$ for diversity transmission $\lambda / 2$ for coherent transmission</td>
</tr>
<tr>
<td>Noise Figure at BS</td>
<td>5 dB</td>
<td>5 dB</td>
</tr>
<tr>
<td>BS antenna gain plus cable loss</td>
<td>14 dBi (micro cell, macro cell)</td>
<td>14 dBi (micro cell, macro cell)</td>
</tr>
</tbody>
</table>

Table 13. Macro BS parameters.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Common assumption in standards</th>
<th>Preferred FREEDOM selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>UE antenna height</td>
<td>1.5 m</td>
<td>1.5 m</td>
</tr>
<tr>
<td>UE transmitted power</td>
<td>23 dBm (200 mW)</td>
<td>23 dBm (200 mW)</td>
</tr>
<tr>
<td>Number of antennas at UE</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Antenna spacing</td>
<td>$\lambda/2$</td>
<td>$\lambda/2$</td>
</tr>
<tr>
<td>Antenna pattern</td>
<td>Omnidirectional</td>
<td>Omnidirectional</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>0 dB</td>
<td>0 dB</td>
</tr>
<tr>
<td>Noise Figure</td>
<td>7 - 9 dB</td>
<td>9 dB</td>
</tr>
<tr>
<td>Cable loss</td>
<td>0 dB</td>
<td>0 dB</td>
</tr>
<tr>
<td>Users distribution</td>
<td>Uniform</td>
<td>Uniform</td>
</tr>
<tr>
<td>Minimum distance UE - BS</td>
<td>$\geq$35 meters</td>
<td>$\geq$35 meters</td>
</tr>
<tr>
<td>UE speeds of interest</td>
<td>3 km/h and 120 km/h</td>
<td>3-6 km/h</td>
</tr>
</tbody>
</table>

Table 14. UE parameters.
### Table 15. FAP parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Common assumptions in standards</th>
<th>Preferred FREEDOM selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum FAP transmit power</td>
<td>20 dBm – for BW of 10 MHz</td>
<td>20 dBm</td>
</tr>
<tr>
<td>Antenna height</td>
<td>1 m</td>
<td>1 m</td>
</tr>
<tr>
<td>Penetration loss outdoor-to-indoor</td>
<td>20 dB</td>
<td>10 dB</td>
</tr>
<tr>
<td>Number of clusters per macro-cell</td>
<td>1, 2, 4 or 10</td>
<td>2 clusters per sector</td>
</tr>
<tr>
<td>Number of femtocells per cluster</td>
<td>FFS</td>
<td>FFS</td>
</tr>
</tbody>
</table>
| Inter-cell interference modelling        | UL: Explicit modelling (all cells occupied by UEs) | a. Explicit modelling  
DL: Explicit modelling else cell power = P<sub>total</sub>  
b. From models provided in section 5.7 or the outcome from activity 3A1 |
| Number of antennas                       | 2 or 4                          | 2                          |
| Antenna spacing                          | $\lambda/2$                     | $\lambda/2$                |
| Number of sectors                        | 1                               | 1                          |
| Antenna gain + connectors loss           | 5 dBi                           | 5 dBi                      |
| Noise Figure at BS                       | 8 dB                            | 8 dB                       |
| Placing of new nodes                     | Clustered FAPs and random placing of UE within X meters of the FAP  
X is FFS  
Clustered FAPs and random placing of UE within FFS (depending on channel model and TX power)  
meters of the FAP | Clusters FAPs and random placing of UE within FFS (depending on channel model and TX power)  
meters of the FAP |
| Minimum distance between UE and FAP      | $\geq3$ m                       | $\geq3$ m                  |
| Minimum distance between FAPs            | FFS                             | According to a statistical model in section 5.2 |
| Backhaul quality model                   | FFS                             | Defined in section 5.8     |
| Access                                   | Closed Subscriber Group (CSG)   | Three modes are considered: CSG, open-access, hybrid-access |
| Target location                          | indoor                          | indoor                     |

### 5.2 Deployment models

Two cases are envisioned to place the femtocells, in a house or in a block of offices. Those two cases address the residential and corporate scenarios of FREEDOM (see sections 2.1.3 and 2.1.1 respectively). The associated parameters are described in Tables 17, 18 and 19. The common parameters for the macrocell layout are shown in Table 16.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Residential area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macrocell layout</td>
<td>Hexagonal grid, 19 cell sites in two cell-rings</td>
</tr>
<tr>
<td>MBS sectorization</td>
<td>3 sectors per site</td>
</tr>
<tr>
<td>Inter-site distance</td>
<td>500 m to 1732 m</td>
</tr>
</tbody>
</table>

Table 16. Descriptors for macrocell layout.
5.2.1 Residential suburban scenario

Residential households are dropped with a random uniform distribution subject to a minimum separation of 6 meters. The density of households is fixed in the scenario and can be extracted from Table 4. Each household area is modeled as a 2D rectangular house plus a surrounding lot (Figure 36).

The fraction of houses hosting an active FAP\(^3\) is a variable in the simulations that will allow evaluating the system performance depending on the FAP penetration. FAP are randomly positioned within each house. UEs are dropped uniformly and randomly in the simulated area, with a density that can be extracted from Table 4. Those UE falling inside the femtocell area are randomly repositioned in such a way that they are placed inside the house with 90% probability. These are labelled as FUE.

UE labelled as MUE are of two kinds: those placed outside the active FAP coverage area, or those inside the coverage area but exceeding the maximum number of FUE per active FAP (1 to 4 table below). Table 17 gives parameters defining the residential femtocell deployment scenario, as well as parameters for a shopping area scenario.

![Figure 36: Femtocell area for residential scenario.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Residential area</th>
<th>Shopping area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FAP areas size</strong></td>
<td>House: 12 m × 12 m</td>
<td>Shopping area: 24m × 24m</td>
</tr>
<tr>
<td></td>
<td>House + Lot : 24 m × 24 m</td>
<td>Shopping area + Lot : 48m × 48m</td>
</tr>
<tr>
<td><strong>Number of floors</strong></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Probability of outdoor FUE</strong></td>
<td>10%</td>
<td>50%</td>
</tr>
<tr>
<td><strong>Distribution of FUEs in FAP area</strong></td>
<td>Indoor FUE: random uniform with a minimum distance to FAP of 20cm.</td>
<td>Outdoor FUE: random uniform outside the house / shopping area</td>
</tr>
<tr>
<td><strong>MUE allowed in the FAP area</strong></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td><strong>Active FUEs per FAP area</strong></td>
<td>Up to 4</td>
<td></td>
</tr>
<tr>
<td><strong>Distribution of FAP areas</strong></td>
<td>Random uniform within macro coverage with a minimum separation of 35m with Macro BS and non-overlapping constraint</td>
<td>Random uniform inside the house / shopping area</td>
</tr>
<tr>
<td><strong>Position of FAP within the FAP area</strong></td>
<td>Random uniform inside the house / shopping area</td>
<td></td>
</tr>
</tbody>
</table>

Table 17. Descriptors for FAP layout in the residential + shopping area scenario.

---

\(^3\) Active FAP are those having at least one active call.
5.2.2 Corporate scenario

Femtocells are deployed in urban building blocks, which are dropped randomly within the macrocell. Each femtocell block is represented by two stripes of offices separated by a street or open stripe of width $w$, as illustrated in Figure 37 with $N=10$ and $w=10$ m as an example. Each office stripe has $2 \times N$ offices (or FAP areas) per floor. Each office is of size $10$ m $\times$ $10$ m. Then the whole femtocell block is of size $(N \times 10$ m) $\times (3 \times w + 40$ m).

Each femtocell block has $L$ floors, where $L$ is randomly distributed between 1 and 10. The separation $w$ between office stripes is fixed, either 10 m to represent dense urban areas with narrow streets, or 25 m to represent mean urban or dense urban with large streets.

A corporate unit is composed of $x$ adjacent offices, thus corporate users can move into different offices.

![Figure 37: A femtocell block for corporate scenario (based on [FemtoForum2010]).](image)

Some studies require investigation of several femtocell scenarios (different femtocell block sizes, different deployment ratios, …) then Table 19 describes the range of values for parameters defining the corporate femto deployment model. Table 19 gives as well specific values for a reference deployment scenario.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of values</th>
<th>Reference value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FAP areas size</strong></td>
<td>Office: 10m × 10m</td>
<td></td>
</tr>
<tr>
<td><strong>Number of FAP areas per floor</strong></td>
<td>2 × N, where N = 5 to 10</td>
<td>2 × 5, i.e. N = 5</td>
</tr>
<tr>
<td><strong>Number of floors</strong></td>
<td>L, random uniformly distributed between 1 and 10</td>
<td></td>
</tr>
<tr>
<td><strong>Open separation</strong></td>
<td>w = 10m or 25m</td>
<td>w = 10m</td>
</tr>
<tr>
<td><strong>Block-FAP area size</strong></td>
<td>(N × 10m) × (3 × w + 40m)</td>
<td></td>
</tr>
<tr>
<td><strong>FAP deployment ratio</strong></td>
<td>0.0 to 1.0</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>FAP Activation ratio</strong></td>
<td>0.0 to 1.0</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Distribution of FAPs within FAP areas (offices)</strong></td>
<td>Random uniform</td>
<td></td>
</tr>
<tr>
<td><strong>Position of the FAP within the FAP area (office)</strong></td>
<td>Random uniform</td>
<td></td>
</tr>
<tr>
<td><strong>MUE allowed in the FAP area</strong></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td><strong>Number of active FUEs per FAP cell</strong></td>
<td>1 to 10</td>
<td></td>
</tr>
<tr>
<td><strong>Distribution of Block-FAP areas</strong></td>
<td>Random uniform within macro coverage with a minimum separation of 35m with Macro BS and non-overlapping constraint</td>
<td></td>
</tr>
<tr>
<td><strong>Number of offices of a corporate unit</strong></td>
<td>Integer uniformly random variable between 1 and 20</td>
<td></td>
</tr>
</tbody>
</table>

Table 18. Descriptors for FAP layout in the corporate scenario.

Some simulations require larger femtocell areas (especially in activity 5A2), then the model presented here above is extended to the multi-block model illustrated in Figure 38 with 2 × 2 blocks and internal courtyard as an example.

Each block is of size (N × 10m) × (N’ × 10m), where N and N’ are between 5 and 20. It is composed of (10m × 10m) offices or femtocell areas, with a possible internal courtyard. Reference values are N = N’ = 5.

When no courtyard is present, the block is composed of N × N’ offices per floor. When a courtyard exists in the center of the block, the block is composed two horizontal stripes and two vertical stripes of offices, of width 20m. The block is composed of (N × (N’-4) × 16) offices per floor. Each block has L floors, where L is randomly distributed between 1 and 10. Two adjacent blocks are separated by a horizontal or vertical street of width w.

UEs are dropped uniformly and randomly within the macrocell, so it is possible that some MUEs are dropped within a FAP area. The labelling of FUE and MUE is the same as in section 5.2.1. In both cases, the MUE floor is random between 1 and 10.
Figure 38: Femtocell multi-block model for corporate scenario.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Office area</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAP areas size</td>
<td>10×10</td>
</tr>
<tr>
<td>Number of FAP areas per floor</td>
<td>5×5</td>
</tr>
<tr>
<td>Number of floors</td>
<td>$L$, random uniformly distributed between 1 and 10</td>
</tr>
<tr>
<td>Block-FAP area</td>
<td>$(5+1)\times10\times(5+1)\times10$</td>
</tr>
<tr>
<td>FAP Deployment ratio</td>
<td>0.2</td>
</tr>
<tr>
<td>FAP Activation ratio</td>
<td>50%</td>
</tr>
<tr>
<td>Distribution of FAP within FAP area</td>
<td>Random uniform</td>
</tr>
<tr>
<td>MUE allowed in the FAP area</td>
<td>Yes</td>
</tr>
<tr>
<td>Number of active FUEs per FAP area</td>
<td>1 to 4</td>
</tr>
<tr>
<td>Distribution of Block-FAP areas</td>
<td>Random uniform within macro coverage with a minimum separation of 35m with BS and non-overlapping constraint</td>
</tr>
</tbody>
</table>

Table 19. Descriptors for FAP layout in a corporate scenario.

5.3 System performance metrics

Simulations could generate various outputs. Similarly, system performance could be evaluated from various standpoints. This subsection proposes a list of common metrics that can be used throughout FREEDOM project.
Depending on the kind of simulation considered, mainly link level or system level simulation, the criteria may differ. Typically, link level simulation considers a single link (one transmitter, one receiver) and performance are evaluated on the basis of bit error rate (BER), or packet error rate (PER) as a function of signal to noise ratio (SNR). Throughput can be evaluated also when for instance link adaptation is considered.

For system level simulation, when multiple cells, multiple users are considered, the system performance metrics are at a higher layer, aggregating results from various users in the cell. Cell throughput, fairness, call drop rate, spectral efficiency and latency could be metrics of interest. For Monte-Carlo based simulations, such equivalence between positions and SNRs could also be established, that could lead to draw map of average coverage.

The following metrics will be considered:

- **Throughput.** The metrics can be measured at the different layers, PHY, MAC and TCP and will be accordingly defined.

  1. The basic one is the **average data throughput** for a single user \( u \), defined as
     
     \[
     R_{ULDL}^{DL(UL)} = \frac{1}{T_{sim}} \sum_{i=1}^{p_{ULDL}^{DL(UL)}} \sum_{j=1}^{q_{ULDL}^{DL(UL)}} b_{j,i,u}
     \]
     which represents the ratio of the number of information bits successfully received divided the total simulation time, \( p_{ULDL}^{DL(UL)} \) is the number of packet calls (up- or down-link), with \( q_{j,i,u}^{DL(UL)} \) packets for the \( i \)-th down- (up-) link packet call and \( b_{j,i,u} \) bits for the \( j \)-th packet.

  2. **Average per-user data throughput** is obtained averaging the above quantity over the users number.

  3. The **sector data-throughput** (DL or UL) is
     
     \[
     R_{sec}^{DL(UL)} = \sum_{u=1}^{N_{sub}} R_{ULDL}^{DL(UL)}
     \]
     where there are \( N_{sub} \) users in the chosen sector, and the \( u \)-th user having throughput \( R_{ULDL}^{DL(UL)} \), for \( u \in N_{sub} \).

  4. The **throughput outage** \( O_{thpt}(R_{min}) \) is the percentage of users with data rate \( R_{ULDL}^{DL} \) less than a predetermined threshold \( R_{min} \).

  5. The **cell edge user throughput**, defined as the 5th percentile point of the CDF of users' average data throughput.

- **Delay metrics.** Several definitions are in order:

  1. **Packet delay** is defined as the temporal difference between the arrival time \( T_{j,i,u}^{arr,DL(UL)} \) of the \( j \)-th packet of the \( i \)-th packet call destined for user \( u \) arrives at the BS (SS) and the delivery time \( T_{j,i,u}^{dep,DL(UL)} \) to the MS (BS) MAC-SAP as
     
     \[
     Delay_{j,i,u}^{DL(UL)} = T_{j,i,u}^{dep,DL(UL)} - T_{j,i,u}^{arr,DL(UL)}
     \]

  2. The **CDF of the packet delay per user** provides a basis in which maximum latency, \( x \%-\)tile, average latency as well as jitter can be derived.

  3. The \( x \%-\)tile packet delay is the packet delay value for which \( x \% \) of packets have delay below this value.

  4. The **CDF of \( x \%-\)tiles of packet latencies** serves to determine the \( y \%-\)tile latency of the \( x \%-\)tile per user packet delays.
5. The $y%$-tile of the $x%$-tile packet delays is the latency number in which $y\%$ of per user $x\%$-tile packet latencies are below this number. This latency number can be used as a measure of latency performance for delay sensitive traffic. A possible criteria for VoIP, for example, is that the 97th %-tile of the 97%-tile of packet latencies per user is 50ms.

6. The average packet delay $D_u^{\text{avg,DL(UL)}}$ for user $u$ is

$$ D_u^{\text{avg,DL(UL)}} = \frac{\sum_{j=1}^{P} \sum_{i=1}^{q_{j,u}} (T_{\text{dep,DL(UL)}} - T_{\text{arr,DL(UL)}})}{\sum_{i=1}^{q_{j,u}}} $$

i.e. the average interval between packets originated at the source station (either MS or BS) and received at the destination station (either BS or MS) in a system for a given packet call duration.

7. The CDF of users’ average packet delay reflects the all users experience.

8. The packet loss ratio is defined as

$$ \text{Packet Loss Ratio} = 1 - \frac{\text{Total Number of Successfully Received Packets}}{\text{Total Number of Successfully Transmitted Packets}} $$

- **Bit error rate (BER):** it measures the performance at the receiver, with or without considered MIMO coding, channel coding or other link layer procedure; the performance is expressed as a function of SNR; interferences could be also taken into account;

- **Packet error rate (PER):** similar to the previous one, but at the packet level; packet could be considered at the output of channel decoder, or potentially after the repetition module if any (ARQ or HARQ);

- **User throughput:** it can be defined the ratio of correctly received information bits on one link to one user for the total simulation time (i.e., the time that elapses in the real system) for this link; it usually includes all the overhead needed for the transmission; however, to evaluate throughput, user satisfaction criteria may be considered (including outage or latency assessment);

- **Cell throughput:** it is the aggregated throughput of all users in the cell;

- **Spectral efficiency:** it represents the cell throughput normalized by the amount of spectrum used in the scenario; once again, clear definition of a satisfied user to evaluate the throughput must be given;

- **Fairness:** fairness can be evaluated on any other criteria for multiple users in a cell; fairness on PER, throughput, latency etc. can be used; to measure the fairness on a specific criteria, the Jain’s fairness index could be used as defined in [JAIN84]; in case of $n$ users competing for something $x$, the Jain’s index $F(x)$ is given by:

$$ F(x) = \left( \frac{\sum_{i} x_i}{n} \right)^2 \left/ \sum_{i} x_i^2 \right. $$

It equals 1 if all users get the same amount of resource, and tends to $1/n$ for fully unfair cases.
It is worth introducing the concept of fairness w.r.t. the required amount of resources. In realistic system co-exist low-rate users (e.g. voice) and high-rate users (e.g. data/video streaming) and the above (Jain) fairness would give the best score to a system that gives excessive resources to the former group and insufficient resources to the latter group. The risk is to give more bandwidth to users requesting low rate services, whereas users requiring higher rate are penalised. To keep into account also the requirements coming from the different requirements distributed among the users. Metrics capable of embedding concepts such as Min-Max Fairness should be considered, as well as metrics that measure the fairness based on the Modified Largest Weighted Delay First (M-LWDF) that (keeping into account the acceptable latency and the QoS) maximises the functional

\[
J_{MLWDF} = -\log \frac{W(u) R(u)}{D(u) T(u)}
\]  

where \( T(u,k) \) has the same meaning and formulation given in the PFS; \( H(u,k) \) is the Head-Of-Line (HOL) latency for the user \( u \) and the beam \( k \); \( D(u) \) is the latency threshold for the user \( u \) and \( \delta_u \) is a scalar such that \( -\log \delta_u / D(u) \) represents the desired QoS level by the \( u^{th} \) user.

- **Handover metrics**

  Specific metrics for the evaluation of handover techniques are defined in section 5.11.2.

### 5.4 Pathloss models

The received signal and interference levels are calculated by different path loss models corresponding to a variety of scenarios considered in macro-femto networks. These radio links, illustrated in Figure 39, can be enumerated as:

- Macro outdoor BS to street-level outdoor UE;
- Macro outdoor BS to indoor UE;
- Indoor FAP to indoor UE, in same building block;
- Indoor FAP to street-level outdoor UE;
- Indoor FAP to indoor UE, in another building block.

![Figure 39: Radio links.](image)

Actually models are classified in two main distinct categories:

- Site-independent (or statistical) path loss models which do not consider any precise terrain description (no building layout, no geographical map data) and any precise terminal location: these models generally consist in simple empirical laws associated to a lognormal
representation of the shadow fading; they are suited to simulation of basic case studies or for stochastic channel modelling in system-level simulations (shadowing is predicted as a random component);

- Site-specific (or deterministic) path loss models that rely on a precise terrain description (building layout, altitude, clutter types, building contours, etc) and precise terminal locations: these models take advantage of the terrain description to simulate part of the shadow fading, approximating the impact of propagation physical mechanisms, then providing realistic and correlated spatial variations of the path loss; they are usually used to predict realistic case studies and for large-scale realistic system-level network simulations (potentially including BSs and FAPs distributed in different situations over the simulation area); one advantage of site-specific path-loss model usage is the intrinsic correlation between different mobile locations and between all simulated radio links.

Path loss models covering both frequency bands investigated in FREEDOM (2.0GHz and 2.6GHz) are described in the following subsections:

- Path-loss models for urban / corporate scenario; composed of site-independent models for the macrocell propagation, and models adjusted to the FREEDOM building block models for small propagation ranges.
- Path-loss models for suburban / residential scenario; composed as well of site-independent models for the macrocell propagation, and models adjusted to the FREEDOM building block models for small propagation ranges.
- Site-specific models for realistic coverage prediction, which takes into account real terrain description.

Some path loss models will be studied in Task 3A1 to enhance solutions dedicated to FREEDOM scenarios (in particular the indoor-outdoor model). The indoor model will also be extended to include the impact of the human activity, i.e. non-stationary components.

Path-loss models given in the two following subsections follow the assumptions:

- Height of the base-station above ground: 32m.
- Frequency: $f = 2000\text{MHz}$ or $2600\text{MHz}$;
- 3D path-length $d$, in meters.

The path-loss $PL$, or mean path-loss, is only one component in the calculation of the received-power:

$$ P_r = EIRP - (PL + \text{Shadowing} + \text{SmallScaleFading}). $$

The shadowing is generally represented by a lognormal component with a fixed standard deviation depending on the propagation scenario. Lognormal standard deviation $\sigma$ and correlation distances of the shadowing component are proposed in the following subsections, partly extracted from the Winner project document [WIND112-1].

The small-scale fading consists in large variations on the scale of a half-wavelength due to the destructive or constructive sum of propagation multi-paths. It is commonly modeled as a random variable from Rayleigh distribution (NLOS) or Rice distribution (one dominant path, e.g. LOS direct-path). These Rayleigh and Rice distributions are characterized by the K factor. The small-scale fading can also be generated from combination of the predicted multi-paths when the propagation model (e.g. ray-tracing) or channel model provides this kind of information.

The received-power is also subject to time-variant fading (considering terminal locations as fixed) due to human or vehicle traffic, which may be significant on all radio links in macro-femto simulations. The impact of human traffic is addressed in activity 3A1.

All details on the elaboration of the path-loss models and comments are available in Appendix A.
### 5.4.1 Urban / corporate scenario

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Recommended path-loss model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro BS to street-level UE (NLOS)</td>
<td>$PL_{macro} = \begin{bmatrix} f_{2.0GHz} \end{bmatrix} 23.8 + \begin{bmatrix} f_{2.6GHz} \end{bmatrix} 20.7 + 20 \cdot \log_{10} (d)$, where $20m \leq d \leq 5000m$.</td>
</tr>
<tr>
<td></td>
<td>Shadowing: lognormal $\sigma = 8$dB; correlation distance 50m.</td>
</tr>
</tbody>
</table>

#### Macro BS to indoor UE

$$PL_{macro-to-indoor} = PL_{macro} - G_p \cdot n_p + L_{2D}$$

- $PL_{macro}$: outdoor path-loss at street level, in dB;
- $L_{2D}$: outdoor-indoor penetration loss, in dB, which is actually highly dependent on the building material, building environment and penetration distance;
- $G_p = 2$dB/floor: floor gain, applicable only for floor height lower than the average building height, i.e. 15m in urban;
- $n_p$: index of the UE floor, assuming 3m floor separation and $n_p = 0$ at the ground-floor; $0 \leq n_p \leq 4$.

For $n_p > 4$, the path-loss is highly dependent on the building environment; we suggest to limit the floor gain to $G_p + 4$.

**Simple approach, uniform penetration loss** (appropriate when no building layout is considered): $L_{2D}$ is an average outdoor-indoor penetration loss, in the range from 10dB (typically for light indoor in sparse urban area) to 20dB (typically for deep indoor in dense urban area).

**Alternative, considering indoor path length:**

$$L_{2D} = L_{2D}^{indoor} + L_{2D}^{outdoor}$$

where $L_{2D}^{indoor}$ is calculated like in the indoor path-loss model (hereafter), depending on the 2D distance $d_{2D}$ between the UE and the closest penetration point. See Appendix A for determination of this penetration point.

**Shadowing:**
- Outdoor-indoor penetration loss: lognormal $\sigma = 5$dB; correlation distance 7m;
- Total: lognormal $\sigma = 9.5$dB.

#### FAP to indoor UE (same office block)

**Single-floor:**

$$PL_{IN-FF} = \begin{bmatrix} f_{2.6GHz} \end{bmatrix} 39.4 + \begin{bmatrix} f_{2.6GHz} \end{bmatrix} 40.7 + 20 \cdot \log_{10} (d) + L_{IN}$$

where $L_{IN}$ are indoor losses, and $1m \leq d$.

**Indoor losses with average linear loss for internal partitions:**

$$L_{IN} = 0.7 \cdot L_{IN}^{1st} + L_{IN}^{2nd} + L_{IN}^{interior}$$

where
- $L_{IN}^{1st}$: average loss through an office separation wall;
- $q_{IN}^{1st}$: number of office separation walls crossed by the direct-path; $q_{IN}^{1st} = 0$ when FAP and UE are located in the same office.

**Indoor losses with simulation of internal office partitions:**

$$L_{IN} = L_{IN}^{1st} + L_{IN}^{2nd} + L_{IN}^{interior}$$

where
- $L_{IN}^{1st} = 5$dB: average loss through an internal office wall;
- \( q_i \): number of office internal walls crossed by the direct-path;
- \( q_i \) is simulated in a random way, following the process described in [R4-071617].

**Multi-floor:**

\[
PL_{IN-HF} = PL_{IN-SF} + 18.3 + \eta_F (\log_2(2 \times (1 + q_i)) / (1 + q_i - 1))
\]

where \( \eta_F \) is the number of floors that separate FAP and UE.

**Shadowing:**

- Lognormal \( \sigma = 4 \text{dB} \) for path-loss model with average linear loss; correlation distance 4m;
- No additional shadowing for path-loss model random internal partitions.

---

**Simple approach, only for UE close to FAP building:**

\[
PL_{IN-OUT} = PL_{IN-SF} + L_{EX}
\]

where \( L_{EX} = 10 \text{dB} \) is the average loss through the external wall.

**Alternative, considering the dominant indoor-outdoor path** (see geometry in Appendix A):

\[
PL_{IN-OUT} = PL_{MICRO} + W_E + W_{2D} \cdot (1 - \sin(\theta))^2 + L_{IN},
\]

where:
- \( d_{IN} \): 2D indoor horizontal path-length, in meters;
- \( D \): 2D outdoor distance, in meters, measured in the direction perpendicular to the external wall;
- \( d_{OUT} \): 3D outdoor path-length, in meters;
- \( \theta \): incidence angle on the external wall; \( \sin(\theta) = \frac{d_{OUT}}{d_{OUT}} \);
- \( W_E = 7 \text{dB} \): penetration loss for normal incidence (i.e. \( \theta = 90^\circ \));
- \( W_{2D} = 20 \text{dB} \): additional loss for grazing incidence (i.e. \( \theta = 0^\circ \));
- \( L_{IN} \): indoor losses calculated from as in the indoor model.

and

\[
PL_{MICRO} = \begin{cases} 
[\text{LOS}] & [2.0 \text{GHz}] \ [35.4 + 20 \cdot \log(d_{IN} + d_{OUT})] \\
[\text{NLOS}] & [2.0 \text{GHz}] \ [46.8 + 40 \cdot \log(d_{IN} + d_{OUT})]
\end{cases}
\]

**Probability** that the penetration wall is in line-of-sight (LOS) or non-light-of-sight (NLOS) from UE may be derived from [ITU1411]. See Appendix A.

**Shadowing:**

- Outdoor contribution: lognormal \( \sigma = 7 \text{dB} \), correlation distance 12m;
- Total: lognormal \( \sigma = 8 \text{dB} \).
Table 20. Path-loss models for corporate scenario.

5.4.2 Suburban / residential scenario

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Recommended path-loss model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro BS to street-level UE (NLOS)</td>
<td>$PL_{MACRO} = \begin{array}{ll} 22.8 &amp; \text{[GHz]} \ 25.1 &amp; \text{[GHz]} \end{array} + 30 \cdot \log_{10}(d)$, where $20m \leq d \leq 5000m$, Shadowing: lognormal $\sigma = 8$dB; correlation distance 50m.</td>
</tr>
</tbody>
</table>
| Macro BS to indoor UE             | $PL_{MACRO-UE} = PL_{MACRO} + L_{DI}$, where 
+ $PL_{MACRO}$: outdoor path-loss at street level, in dB; 
+ $L_{DI}$: outdoor-indoor penetration loss, in dB, which is actually highly dependent on the building material, building environment and penetration distance. 
Simple approach, uniform penetration loss (appropriate when no building layout is considered): $L_{DI}$ is an average outdoor-indoor penetration loss, in the range from 10dB (typically for light indoor in sparse suburban area) to 20dB (typically for deep indoor in dense suburban area).
Alternative, considering indoor path length: 
$L_{DI} = 13dB + L_{IN}$
where $L_{IN}$ is calculated like in the indoor path-loss model (hereafter), depending on the 2D distance $d_{2D}$ between the UE and the closest penetration point. See Appendix A for determination of this penetration point.
Shadowing: 
+ Outdoor-indoor penetration loss: lognormal $\sigma = 5$dB; correlation distance 7m; 
+ Total: lognormal $\sigma = 9.5$dB.
<table>
<thead>
<tr>
<th>Case</th>
<th>Formula (if any)</th>
</tr>
</thead>
</table>
| **FAP to indoor UE (same house)**         | \[PL_{\text{IN-2F}} = [2.6\,\text{GHz}] 38.4 + 20 \cdot \log_{10}(d) + L_{\text{IN}}\]  
   \[L_{\text{IN}} \text{ are indoor losses, and } 1\text{m} \leq d\]  
   **Indoor losses with average linear loss for internal partitions:**  
   \[L_{\text{IN}} = 0.7 \cdot d_{\text{IN}}\]  
   **Indoor losses with simulation of internal office partitions:**  
   \[L_{\text{IN}} = L_1 \cdot q_1, \text{ where}\]  
   \[- L_1 = 5\,\text{dB}: \text{average loss through an internal office wall;}\]  
   \[- q_1: \text{number of office internal walls crossed by the direct-path;}\]  
   \[- q_1 \text{ is simulated in a random way, following the process described in [R4-071617].}\]  
   **Multi-floor:**  
   \[PL_{\text{IN-MF}} = PL_{\text{IN-2F}} + 18.2 \cdot n_F\]  
   \[n_F \leq 1\text{ is the number of floors that separate FAP and UE.}\]  
   **Shadowing:**  
   \[- \text{Lognormal } \sigma = 4\,\text{dB for path-loss model (17); correlation distance } 4\text{m;}\]  
   \[- \text{No additional shadowing for path-loss model (18).}\] |
| **FAP to outdoor street-level UE**         | Similar to urban / corporate scenario. |
| **FAP to indoor UE (other office block)**  | Similar to urban / corporate scenario. |

### Table 21. Path-loss models for residential scenario.

#### 5.4.3 Site-specific models

Site-specific models are used in WP5 for realistic coverage predictions, and WP3 for study of the indoor-to-outdoor channel or human activity impact.
### Configuration

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Recommended path-loss model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro BS to street-level UE</td>
<td>Multiple knife-edge diffraction method (e.g. Deygout). Or 3D ray-tracing (include simulation of multi-paths) [COR09].</td>
</tr>
<tr>
<td>Macro BS to indoor UE</td>
<td>The outdoor contribution(s) is predicted at the UE floor height by the macro model. The penetration loss and indoor loss depend on the building representation (only contours, only main separations, or all internal partitions) [LOS06]. Distinction is made between penetration through a window, a door or a wall.</td>
</tr>
<tr>
<td>FAP to indoor UE (same office block)</td>
<td>COST231 multi-wall model with possible representation of all internal partitions.</td>
</tr>
<tr>
<td>FAP to outdoor street-level UE</td>
<td>The indoor loss and outdoor-indoor loss depend on the building representation (only contours, only main separations, or all internal partitions). Distinction is made between penetration through a window, a door or a wall. The outdoor contribution is predicted by ray-tracing.</td>
</tr>
<tr>
<td>FAP to indoor UE (other office block)</td>
<td>Idem.</td>
</tr>
</tbody>
</table>

#### Table 22. Site-specific path-loss models.

### 5.5 Channel models

**Tapped Delay Line (TDL) models**, originally designed for narrowband single input single output (SISO) systems, are widely used for link-level simulations. ITU-R M.1225 recommendation [ITU1225] defines 6 different channel models composed of 6 taps associated to a delay, average power and Doppler spectrum class (flat or classic), adapted to indoor office (Indoor office A and B), pedestrian reception or outdoor-indoor (Pedestrian A and B) and vehicular reception (Vehicular A and B). In particular, the WiMAX Forum makes use of the ITU Vehicular A and ITU Pedestrian B channels.

SUI channel models, proposed by IEEE 802.16 group for fixed broadband wireless systems [SUI01], provide 6 typical channels for three types of terrain (category A: hilly terrain with moderate-to-heavy tree density, category C: flat terrain with light tree density, category B: intermediate conditions) with parameters adapted either to omni or 30° directional antenna. SUI channel models define for each tap the delay, average power, K factor and maximum Doppler frequency. MIMO systems are considered by introducing correlation between input and/or output multiple signals.

**Besides, Geometry-based stochastic channel models (GSCM)** propose solutions adapted to different multiple-antenna technologies. They are generally based on the construction of scatterers distributed into clusters, providing random space-time channel simulations with correlation between channel parameters (shadowing, delays, departure angles and arrival angles).

- The Spatial Channel Model (SCM) by 3GPP defines three different types of environment: suburban macro, urban macro and urban micro. It is originally intended to 2GHz systems with up to 5MHz maximum bandwidth. The SCME (SCM-extended) model is extended to 5GHz systems, supports bandwidths up to 100MHz and includes time-variant shadow fading, angles and delays for system-level simulation [Baum05]. It features as well a reduced-variability tapped delay-line model for usability in calibration and comparison purposes.
- The WINNER II channel model [WIND112-1 and WIND112-2] can be applied to any wireless system operating on the frequency range from 2GHz to 6GHz with up to 100MHz bandwidth. A
wide range of scenarios is defined, including indoor office or residential, indoor-to-outdoor, outdoor-to-indoor, urban microcell, urban macrocell, suburban macrocell and rural macrocell. A Cluster Delay Line (CDL) model is proposed as a complement to the generic model with cluster properties set from tables, being suitable for calibration and comparison purposes.

The WINNER II channel model is the one recommended for FREEDOM simulations, as it is suitable for both 2.0GHz and 2.6GHz and most of femto scenarios: connection between the WINNER II scenarios and the FREEDOM radio configurations is made in Table 23. The CDL model may be used in some reference simulations, whereas the generic model must be employed for stochastic link-level and system-level simulations.

<table>
<thead>
<tr>
<th>FREEDOM configuration</th>
<th>WINNER II channel model - Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro BS to street-level UE</td>
<td>C1: Suburban macro-cell.</td>
</tr>
<tr>
<td></td>
<td>C2: Typical urban macro-cell (building height and</td>
</tr>
<tr>
<td></td>
<td>density are mostly homogenous).</td>
</tr>
<tr>
<td></td>
<td>C3: Bad urban macro-cell (building heights and</td>
</tr>
<tr>
<td></td>
<td>densities are inhomogeneous, which is modeled by</td>
</tr>
<tr>
<td></td>
<td>additional far scatterers).</td>
</tr>
<tr>
<td>Macro BS to indoor UE</td>
<td>C4: Outdoor to indoor macro-cell</td>
</tr>
<tr>
<td>FAP to indoor UE (same building)</td>
<td>A1: Indoor office / Residential.</td>
</tr>
<tr>
<td>FAP to outdoor street-level UE</td>
<td>A2: Indoor to outdoor.</td>
</tr>
<tr>
<td>FAP to indoor UE (other building)</td>
<td>N/A.</td>
</tr>
</tbody>
</table>

Table 23: Relation between the FREEDOM radio configurations and WINNER 2 scenarios.

5.6 Traffic models

In the following, some well-known traffic models considered in FREEDOM project are presented. The majority of traffic models presented here is based on the Deliverable 1D1 “Report on Operational Scenarios and Simulation Methodology” of the IST-ROCKET project [ROCKET_1D1], the draft of IEEE 802.16m evaluation methodology [IEEE802.16m_EMD], and the draft “Guidelines for evaluation of radio interface technologies for IMT-Advanced” [ITU1225].

Besides sophisticated traffic models, a Full Queue Model when all users in the system have always data to send or receive will be used. In other words, there is always a constant amount of data that needs to be transferred, in contrast to bursts of data that follow an arrival process. This model allows the assessment of the spectral efficiency of the system independently of actual user traffic distribution type.

5.6.1 VoIP Model

VoIP refers to a real-time delivery of voice packet across networks using the Internet protocols. A VoIP session is defined as the entire user call time and VoIP session occurs during the whole
simulation period. A typical phone conversation is marked by periods of active talking interleaved by silence/listening period as shown in Figure 40.

A two state Markov process (active-inactive) is used to model a VoIP source. The alternating periods of activity and silence are exponentially distributed with average durations of $1/\beta$ and $1/\alpha$ respectively. Each active state period can be treated as a packet call and inactive period as the OFF period within a session. During the active state, packets of fixed sizes are generated at a regular interval. The size of packet and the rate at which the packets are sent depends on the corresponding voice codecs and compression schemes.

During the inactive state, a comfort noise with smaller packet sizes is generated at a regular interval instead of no packet. Parameters associated with the VoIP traffic model can be found in Table 24.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Parameters</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Active state duration</strong></td>
<td>Exponential</td>
<td>Mean = 1 second</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$f_x = \lambda e^{-\lambda x}, x \geq 0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\lambda = 1/\text{Mean}$</td>
</tr>
<tr>
<td><strong>Inactive state duration</strong></td>
<td>Exponential</td>
<td>Mean = 1.5 second</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$f_x = \lambda e^{-\lambda x}, x \geq 0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\lambda = 1/\text{Mean}$</td>
</tr>
<tr>
<td><strong>Probability of transition from</strong></td>
<td>N/A</td>
<td>$\mu = 0.6$</td>
</tr>
<tr>
<td>active to inactive state</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Probability of transition from</strong></td>
<td>N/A</td>
<td>$\mu = 0.4$</td>
</tr>
<tr>
<td>inactive to active state</td>
<td></td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 24. Parameters of VoIP model.

5.6.2 FTP model

File transfer traffic is characterized by a session consisting of a sequence of file transfers, separated by reading times. The reading time is defined as the time between the end of the transfer of the first file and the transfer request for the next file. The packet call size is therefore equivalent to the file size and the packet call inter-arrival time is the reading time.

A user of FTP service is defined to be in outage if the average packet call throughput is less than the minimum average throughput requirement of 128 kbps. The system outage requirement is such that no more than 2% of users are in outage. All parameters, mean and variance of the distribution functions as well as the transformed mean and variance values are summarized in Table 25.
### 5.6.3 HTTP model

HTTP traffic characteristics are governed by the structure of the web pages on the internet, and the nature of human interaction with web pages. This nature defines the HTTP traffic as a bursty time structure, where the HTTP traffic is characterized by ON/OFF periods. The ON periods represent the sequence of time slices in which the web page is being transferred from source to destination; while the OFF periods represent time slices in which the user reads the webpage, before making some action such as transitioning to another page. This time is also known as Reading Time (see Figure 41).

#### Table 25. FTP traffic model parameters.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Parameters</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>File size ($S$)</td>
<td>Truncated lognormal</td>
<td>$f_s = \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right], x \geq 0$</td>
</tr>
<tr>
<td></td>
<td>Mean = 2 Mbytes</td>
<td>$\mu = 14.45, \sigma = 0.35$</td>
</tr>
<tr>
<td></td>
<td>Max = 5 Mbytes</td>
<td>If $x&gt;$max or $x&lt;$min, discard and generates new value</td>
</tr>
<tr>
<td>Reading time ($D_{re}$)</td>
<td>Exponential</td>
<td>$f_r = \lambda e^{-\lambda x}, x \geq 0$</td>
</tr>
<tr>
<td></td>
<td>Mean = 180 second</td>
<td>$\lambda = 0.006$</td>
</tr>
</tbody>
</table>

#### Figure 41. HTTP traffic pattern.

The amount of information passed from the source to destination during the ON period is governed by the web page structure. A web page is usually composed of a main object and several embedded objects. The size of the main object, in addition to the number and size of the embedded objects define the amount of traffic passed from source to destination. HTTP model parameters are described in Table 26.
<table>
<thead>
<tr>
<th>Distribution</th>
<th>Parameters</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main object size (SM)</strong></td>
<td>Truncated lognormal</td>
<td>[ f_x = \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left[ -\frac{(\ln x - \mu)^2}{2\sigma^2} \right], x \geq 0 ] [ \mu = 8.37, \sigma = 1.37 ] If x&gt;max or x&lt;min, discard and generate new value</td>
</tr>
<tr>
<td><strong>Embedded object size (SE)</strong></td>
<td>Truncated lognormal</td>
<td>[ f_x = \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left[ -\frac{(\ln x - \mu)^2}{2\sigma^2} \right], x \geq 0 ] [ \mu = 6.17, \sigma = 2.36 ] If x&gt;max or x&lt;min, discard and generates new value</td>
</tr>
<tr>
<td><strong>Number of embedded objects per page (Nd)</strong></td>
<td>Truncated Pareto</td>
<td>[ f_x = \frac{k^a}{x^{a+1}}, k \leq x &lt; m ] [ f_x = \left( \frac{k}{m} \right)^a, x = m ] [ \alpha = 1.1, k = 2, m = 55 ] Subtract from the generated random value to obtain Nd. If x&gt;max or x&lt;min, discard and generates new value</td>
</tr>
<tr>
<td><strong>Reading time (Dpc)</strong></td>
<td>Exponential</td>
<td>[ f_x = \lambda e^{-\lambda x}, x \geq 0 ] [ \lambda = 0.033 ]</td>
</tr>
<tr>
<td><strong>Parsing time (Tp)</strong></td>
<td>Exponential</td>
<td>[ f_x = \lambda e^{-\lambda x}, x \geq 0 ] [ \lambda = 7.69 ]</td>
</tr>
</tbody>
</table>

Table 26. HTTP model parameter.

5.6.4 Gaming Traffic Model

Gaming traffic is generated by users (located in different places) engaged in interactive multiple player gaming via the internet. A gaming session occurring during the whole simulation period is defined as the time period within which a user plays a game.

The packet arrival time and the frame boundary are random and shall be simulated. Gaming packets are relatively small in size. Due to the interactive nature of gaming, packet delay must be short. Gaming traffic model parameters for DL and UL can be found in Table 27. Largest Extreme Value distribution is used for random packet size generation. Since packet size has to be an integer, the largest integer less than or equal to X is used as the actual packet size.
5.6.5 Traffic Mix

A mobile broadband wireless system is expected to support a mix of simultaneous traffic types. There can be different types of usage scenarios (multi-service vs. single type), different types of devices (notebook PCs, vs. PDAs or smart phones), different usage levels (intense vs. light) and different delay/latency requirements (real-time vs. best-effort). The previous sections are primarily concerned with the traffic models for each of the potential traffic types.

In the context of system performance evaluation, the specific traffic mix chosen should emphasize different aspects of the system performance, e.g. sustained throughput for file downloads vs. faster response times for interactive applications.

Table 28 contains traffic mixes that are used for system evaluation within the FREEDOM project. For system level simulation purposes, “traffic mix” refers to the percentage of users in the system generating a particular type of traffic. In this context, each user is assumed to generate only one type of traffic, recognizing that in an actual network a single UE could support multiple applications and generate several types of traffic simultaneously. Mandatory traffic mixes (full buffer data only and VoIP only) shall be required for the evaluation of performance metrics as defined in the IMT-advanced requirements.

<table>
<thead>
<tr>
<th>Traffic Mix Type</th>
<th>WWW</th>
<th>File Transfer</th>
<th>VoIP</th>
<th>Gaming</th>
<th>Full Buffer</th>
<th>Mandatory/Optional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Buffer Data only</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>Mandatory</td>
</tr>
<tr>
<td>VoIP only</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>Mandatory</td>
</tr>
<tr>
<td>Gaming only</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>0%</td>
<td>Optional</td>
</tr>
<tr>
<td>Mix 1</td>
<td>10%</td>
<td>30%</td>
<td>60%</td>
<td>0%</td>
<td>0%</td>
<td>Optional</td>
</tr>
<tr>
<td>Mix 2</td>
<td>50%</td>
<td>20%</td>
<td>30%</td>
<td>0%</td>
<td>0%</td>
<td>Optional</td>
</tr>
</tbody>
</table>

Table 28. Traffic mixes.
5.7 Interference power models

A fundamental issue in femtocell systems is interference management. While operating FAPs on dedicated frequency channels is a pragmatic possibility to prevent interference, co-channel operation with an existing macro-network is technically far more challenging, but can yield a significant increase in spectral efficiency per area through spatial frequency re-use. The price to be paid for using a co-channel operation mode is the increase of aggregated self-interference that is the interference coming from nodes belonging to the same network. In such a scenario, the key challenge is to keep the interference increase caused by FAPs low enough to ensure a low impact on the performance of the existing macro-network, but still use enough transmit power for FAPs to achieve high data rates. An approach useful to limit the interference in these systems is to equip the FAPs with spectrum sensing capabilities, thereby enabling them to autonomously detect spectral opportunities and react to the time-varying spectrum usage. In this way, cognitive FAPs dynamically access the unused bands, commonly referred to as white spaces. A critical step in this process is the detection performed by FAPs over the set of sensed channels. In particular, the choice of a detection threshold has a direct impact on the probability of missing transmission opportunities, on one side, as well as on the generation of undue interference toward other FAPs or Macro BS, on the other side. The joint optimization of detection thresholds and power allocation in a multiuser multicarrier scenario was recently addressed in [Barbarossa09]. Interference in wireless communications systems can be modeled according to two alternative and complementary approaches: deterministic or stochastic. In the following, we will outline the basic properties of the modeling strategies, as relevant for femtocell systems.

5.7.1 Deterministic Models

One way to address the problem of interference characterization in wireless networks is to use a deterministic channel model, which attempts to model the signal propagation and distortions for specified transmitter-receiver geometries, terrain types, and antennas. A typical deterministic model used in radio-propagation analysis is ray tracing. It is a method for calculating the path of waves through a system with regions of varying propagation velocity, absorption characteristics, and reflecting surfaces. Under these circumstances, wave fronts may bend, change direction, or reflect off surfaces, complicating analysis. When applied to problems of electromagnetic radiation, ray tracing often relies on approximate solutions of Maxwell’s equations that are valid as long as the electromagnetic waves propagate through and around objects whose dimensions are much greater than the wavelength. Using this approach, it is possible to describe the wireless channel in a deterministic manner, and then received signal once set environment parameters, and evaluate interference characteristics. However, such a characterization is specific of a given channel scenario and, as such, it cannot be used to assess the performance of a wireless channel, in general, because its validity is bounded to the specific geometries, terrain types, antennas and transmitter-receiver geometries, assumed as a reference.

A deterministic approach is useful to evaluate the behavior of hand-over systems (see, e.g., Section 3.1.4). In such case, in fact, it is necessary to simulate a mobility model, within a given geometry scenario. This requires the specification of the FAPs’ and Macro BSs’ positions and number, the environment surrounding transmitter and receiver, and the incorporation, within such a geometry, of an appropriate mobility model (see, e.g., Table 5 in 3.1.5). In this case, it is useful to generate the received signal and the interference using a deterministic approach, e.g., using a ray tracing technique and check the performance of the hand-over technique as time progresses.

5.7.2 Stochastic Models

In practice, except for some simplified cases, the received signal is the result of a complicated interaction between the radiated electromagnetic wave and the environment between transmitter and receiver. Such an interaction is typically too complicated to be described in a deterministic way. Hence, the only way to describe the general properties of a wireless channel is in probabilistic terms. If we consider a femtocell deployment scenario, interference analysis is further complicated by the complexity of the propagation environment and by the random nature of the users’ positions. In general, there are more sources of randomness:
• number and position of transmitting and receiving nodes;
• channel fading, including path losses, multipath, shadowing, diffraction, etc.;
• interferers’ activity.

These considerations have led to the proposal of several statistical models to estimate the amount of interference in wireless systems. The path loss over a wireless link is well modeled by the product of a distance component (often called large-scale path loss) and a fading component (called small-scale fading or shadowing). It is usually assumed that the distance part is deterministic while the fading part is modeled as a random process. However, in a femtocell scenario, there may be interference coming from several FAPs transmitting over the same bands. In such a case, two sources of randomness combine into the same observed phenomenon: the transceiver positions and the fading process. In this case, it is useful to consider a doubly stochastic channel model that incorporates both. A largely accepted model used to characterize the node spatial distribution in wireless networks is the Poisson Point Process (PPP), as it represents a good trade-off between complexity and capability to describe realistic situations. In this section, we report the main results in literature useful to characterize the aggregated interference, in a statistical sense. These models can be adopted to model the interference that a UE perceives from the downlink communications of the Macro BS and of the FAPs (toward other UEs) close to its spatial position. Surely, the models are valid also for the correspondent uplink case where the Macro BS or a FAP perceives interference from the UL communication (toward other FAPs or Macro BS) of close UEs. In [Baccelli09] a stochastic analysis of interference in wireless networks, is provided. Before expressing interference stochastic characterization, let’s introduce some concept that will be useful below.

5.7.2.1 Marked Point Processes and Shot-Noise Field

In a marked point process (m.p.p.), a mark is attached to each point. This mark reflects a statistical property of the node. If we consider a Euclidean space $\mathbb{R}^d$ with $d \geq 1$, as the space of the point process, and a second space $\mathbb{R}^l$, $l \geq 1$, called the space of marks, a marked p.p. $\Phi$ with points in $\mathbb{R}^d$ and marks in $\mathbb{R}^l$, is a locally finite, random set of points in $\mathbb{R}^d$, with some random vector in $\mathbb{R}^l$ attached to each point. A marked point process can be represented as a collection of pairs $\hat{\Phi} = \{(x_i, m_i)\}$, where $\Phi = \{x_i\}$ is the set of points and $\{m_i\}$ the set of marks. A marked p.p. is said to be independently marked if, given locations of the points, the marks are mutually independent random vectors in $\mathbb{R}^l$, and the conditional distribution of the mark $m$ of a point $x$ depends only on the location of this point $x$ it is attached to.

For statistical interference modeling, it is also useful to recall the definition of shot noise, associated to a m.p.p. A shot-noise field is a non-negative vector random field $I_{\Phi}(y)$ defined for all $y$ in some Euclidean space and which is a functional of a marked point process $\Phi$. Moreover, the case the field lives in the same space of the point process is the most common. The term “shot-noise” comes from this special case with $d=1$.

A shot-noise in time assumes the form

$$X(t) = \sum_i g(t - t_i)$$

and can be considered as the output of a linear time-invariant system with impulse response $g(t)$ and input a Poisson sequence of impulse $z(t) = \sum_i \delta(t - t_i)$ [Papoulis65]. The inter-arrival times expressed by $\Delta t_i = t_{i+1} - t_i$ have an exponential distribution.
If we consider a spatial Poisson sequence of impulse $z(r) = \sum_i \delta(r - r_i)$ as input, (1) becomes

$$X(r) = \sum_i g(r - r_i)$$

(9)

In the 2D case, the distance between nodes located according to a p.p.p. have a Rayleigh distribution.

In the case of a shot-noise $I(y) = I_\Phi(y)$, generated by an i.m. PPP $\Phi$, the distribution of the shot-noise vector $I(y)$ is known in terms of its multivariate Laplace transform [Baccelli09].

### 5.7.2.2 Interference Field as Shot-Noise

We are now able to characterize the interference field as a (marked) shot noise. Let’s consider a collection of transmitters distributed in the space and sharing a common radio medium and assume that signal attenuation depends on distance and some stochastic ingredients (typical of a femtocell deployment scenario). The total power received from this collection of transmitters at a given location can be modeled as a shot-noise field. For instance, in the case of a planar point distribution, with omni-directional antennas, the simplest model consists of:

1. A collection of points $\{x_i\}$ representing the locations of transmitters on the plane;
2. Marks $m_i = p_i$ representing the power of the transmitters;
3. A scalar response function $L(y, x, p) = p/l(|x - y|)$, where $l$ is the omni-directional path-loss function, assumes the role of the filter impulse response.

As we shall see, additional elements of the radio wave propagation model (antenna azimuth, random fading model, etc.) can be taken into account by enriching the marks of the point process. The total power received from a set of transmitters scattered in the plane can often be considered as interference or noise with respect to the signal received from one (or more) transmitters(s) not belonging to this set. The fact that the interference field of such a set of transmitters can be interpreted as a shot-noise field opens new ways of accessing its statistical properties. In fact, in the same way as Rayleigh fading was shown to be an efficient statistical model better suited to assessing the fluctuations of a multipath channel than solving the electromagnetic field equations, the shot-noise model can be seen as an efficient statistical model for predicting the fluctuations of the interference field. In a standard stochastic scenario, we consider a marked point process $\Phi = \{(x_i, p_i)\}$ with $\{x_i\} \in \mathbb{R}^2$ transmitters and $p_i \in \mathbb{R}^+$ emitted powers, with an omni-directional path-loss function $l$, modeled as:

$$I(r) = 1 + \left(\frac{r}{r_0}\right)^\beta$$

(10)

for some $r_0 > 0$, $\beta > 2$, where $\beta$ is the path-loss exponent and we assume the signals are transmitted and received by omni-directional antennas. Hence, the total power received at some location $y$ is

$$I(y) = I_\Phi(y) = \sum_{(x_i, p_i) \in \Phi} \frac{p_i}{l(|y - x_i|)} , \quad y \in \mathbb{R}^2.$$  

Furthermore in a standard stochastic scenario we assume that:

1. $\Phi$ is stationary independently marked point process (i.m.p.p.) with points in $\mathbb{R}^2$ and intensity $\lambda$;
2. The marks have a distribution $P\{p \leq s\} = G(s)$ that does not depend on the location of the points.

We call the above stochastic scenario of shot-noise a GI/GI interference model, where the first GI denotes a general independently marked stationary point process and the second GI stands for a general mark distribution. Some special cases are:
- M/* if the underlying i.m.p.p. $\Phi$ is Poisson;
- D/* if $\Phi$ is deterministic;
- */M if the marks are exponentially distributed;
- */D if the marks are deterministic and constant.

For instance the interference field in a mobile ad-hoc network (MANET) with nodes located according to a Poisson p.p. and without power control can be seen as a M/* shot-noise. Similarly, the famous honeycomb model used in certain cellular network models for representing the location of Macro BSs leads to a downlink interference field, which falls in the D/* shot-noise provided no power control is used. In this way we have a stochastic model that describes our deployment scenario (a FUE/FAP that perceives interference DL/UL, from different FAPs/FUEs) and incorporates an independently marked point process $\Phi$, that describes interferers locations in $\{x_i\}$, fading in $m_i$ and packet arrival rate.

5.7.2.3 Packet arrival rate

In a spatial Poisson point process, let $S$ be a subset of $\mathbb{R}^n$ (in our case, for simplicity let’s consider $n=2$), and let $A$ be the family of subsets $S$. We will denote with $N(A)$ the number of points in set $A$, and with $|A|$ the size of $A$ (in $\mathbb{R}^2$ is the area, in $\mathbb{R}^3$ is the volume). For a spatial Poisson point process, if $A_1, A_2, \ldots, A_n$ are disjoint regions, the probability distribution of $N(A)$ depends on the set $A$ only through its size $|A|$. Then the probability to have $N(A) = k$ is:

$$p_k = p(N(A) = k) = e^{-\lambda |A|} \frac{\lambda^k |A|^k}{k!}$$

where $\lambda$ denotes the node density.

To incorporate the packet arrival rate in the model, we have to know how many users are active at the same time, among the potential interferers ($N(A)$). For this reason we introduce a probability $p_i^\text{act}$ that the $i$-th user is active. Let’s now consider a new point process (marked), with marks given by $p_i^\text{act}$. It is possible to prove that, if the marks are i.i.d., and if we consider that users are transmitting with probability $\mu$ ($p_i^\text{act} = \mu$), then the resulting (marked) point process, that considers all points $\{x_i\}$ with marks $p_i^\text{act} = \mu$, is still a Poisson one and it has intensity given by $\lambda p^\text{act}$.

Then, (4) is modified as follows:

$$p_{\text{act}} = e^{-\lambda p_{\text{act}} |A|} \frac{\lambda p_{\text{act}} |A|^k}{k!}$$

and it expresses the probability to have $k$ active users at the same time. Multiplying (5) for users’ packet transmission rate we can evaluate packet arrival rate at location $y$.

Now, if we consider a femtocell deployment scenario, let’s assume that emitted powers $p_i = p$ are constant (this could be a reasonable choice if we consider the DL interference perceived by a FUE located in $y$ from several (i) FAPs with random positions in the plane $\{x_i\}$). Then the power received at the location $y$ from a transmitter at $x_i$ is equal to $p F_i / |y - x_i|$, where $F_i$ is an exponential random variable with mean 1. Thus interpreting $p F_i$ as a ‘virtual power’ (which is hence exponential with mean $p$), the GI/M model may be used to describe the interference in the presence of Rayleigh fading. For analytical expressions regarding first and second order moments of interference, see [Baccelli09]. The main result of this analysis is that for a path loss model as in (3), the mean converges to finite value if $\beta > 2$, otherwise converges if $r$ is upper bounded. This would be a
reasonable choice in our deployment scenario, where each receiver has SINR cell defined as the set of locations where the SINR of the channel from an interferer \( X \) to the receiver \( y \) is larger than a given threshold \( t \). However \( E[F(y)] < \infty \).

### 5.7.2.4 Fading

Let’s now consider the joint law of an interference field generated by transmitters located as a Poisson point process, incorporating a Rayleigh fading channel model. To model the actual received power, it is useful to introduce a random fading field \( F = F(x, y) \), which reflects the multipath signal propagation from \( x \) to \( y \). It is then natural to introduce the response function \( L(x, y, p) = pF(x, y)/l(|x - y|) \) in the shot-noise description of the interference field. Consequently, a shot-noise model incorporating fading takes the form:

\[
I(y) = I_\Phi(y) = \sum_{(x_\ell, y_\ell, r_\ell) \in \Phi} \frac{p_\ell F_\ell(y)}{l(|y - x_\ell|)}
\]

where \( F_\ell(\cdot) = F(x_\ell, \cdot) \). According to [Baccelli09], it is possible to evaluate the characteristics of the interference field in (4) at one location. In this case only distribution of the vector \( (F_\ell = F(x_\ell, y_\ell) : x_\ell \in \Phi) \) is required. Moreover it is i.i.d. at least if the mean nearest neighbor distance for the point process \( \Phi \) is much larger than a given \( \Delta \) that’s of the order of wavelength. Thus, taking a standard model with \( p_\ell = pF_\ell \), captures the fading effect well.

We can conclude that modeling interference as shot-noise provides interference spectral and correlation properties. These latter are really important because permit us to evaluate the interference coherence time. In fact the power spectrum \( S_\alpha(\omega) \) of (2) is known (has an impulse for \( \omega = 0 \) and then a trend that depends on \( g(r) \)). Once obtained \( S_\alpha(\omega) \), it is possible to obtain the autocorrelation function of \( X(r) \), \( R_\alpha(r) \) as the inverse Fourier transform of \( S_\alpha(\omega) \) (see, e.g. [Papoulis65]). Using a path loss model as in (3) we are able to evaluate the Fourier transform of \( g(r) \). In this way we can evaluate interference coherence time defined as the time interval \( T_c \), in which the interference may be assumed fairly constant. In formulas, considering a second order stationary process, with autocorrelation function \( R_\alpha(t_1, t_2) \) that depends only on \( r = t_2 - t_1 \), the coherence time is defined as:

\[
T_c = \{r = T_c : R_\alpha(r) \geq R_\alpha(0)/2\}
\]

For example, considering (2), with a function \( g(r) \) as in (3) with \( \beta = 2 \) then, as \( r = \nu t \), with \( \nu \) signal speed, spectrum is \( S_\alpha(\omega) = \frac{2\pi \beta^2 \nu^2}{4\nu^2} \delta(\omega) + \frac{\beta^2 \nu^2}{4\nu^2} e^{-2\beta \nu |\omega|} \), and autocorrelation function is given by:

\[
R_\alpha(r) = \frac{\beta^2 \nu^2}{4\nu^2} + \frac{\beta^2 \nu^2}{4\nu^2} e^{-4\beta \nu r / \nu^2 + r^2}. \]

From the latter, it is possible to evaluate coherence time \( T_c \).

Finally, a fairly general expression for the interferer signal \( i(t) \), received by a FUE located at a position \( y \) can be written as:

\[
i(t) = \sum_{i=1}^{N_\nu} g(\|Y - Z_i\|) H_i(t) X_i(t) = \sum_{i=1}^{N_\nu} \frac{1}{\sqrt{1 + \left( \frac{r_i}{\nu} \right)^\beta}} H_i(t) X_i(t)
\]

where \( N_\nu \) is the number of interferers, \( X_i(t) \) is the signal transmitted by the i-th user, \( g(\|Y - Z_i\|) = g(r) \) incorporates the path-loss model, \( H_i(t) \) is the fading channel, \( Z_i \) is the location of the i-th transmitter, and \( r_i = \|Y - Z_i\| \). In the limiting case of \( N_\nu \) going to infinity, modeling a high number of interferers, the previous expression allows a theoretical analysis useful to evaluate the
interference coherence time, a parameter that plays a key role in interference management and in the design of the most appropriate radio access strategies.

5.8 **Backhaul quality models**

5.8.1 **Issues in backhaul quality**

Femtocell deployments address the use of shared broadband IP links that connect the FAPs installed in residential or office area to the core network of a cellular operator. Compared to the typical macrocell backhaul links which are guaranteed under a SLA/SLG agreement, a shared broadband IP link may have lower performance in terms of average data rate, latency, jitter and packet loss. Backhaul capacity for a 4G macrocell as suggested by NGNM Alliance requires 450 Mbps for downstream and 150 Mbps upstream per site [NGNM01]. As a FAP is designed to support 4-5 users, the backhaul capacity requirement can be reduced and optimised based on typical service traffic model, per users data rate needs (1 Mbps – 5 Mbps) and affordable broadband IP link price in the retail market.

If the cellular operator and broadband links provider come from the same company group, the performance of broadband link can be coordinated and controlled under internal agreement. This case refers to an integrated operator model. If the cellular operator reuses an existing broadband IP link offered by a third party Internet Service Provider (ISP) there is a little coordination of QoS possible on the IP links. In order to guarantee end-to-end QoS performance, the SLA/SLG may be introduced with the additional cost for the new SLA, hence increasing overall OPEX of femtocell.

Compared to the research in air-interface aspects, the study of backhaul quality model for 4G femtocell is still limited. A comprehensive femtocell deployment guideline considering backhaul quality for 3G femtocell was addressed in [EPITIR01]. The guideline addressed the quality issue of VoIP services over 3G femtocell networks. VoIP services were observed as representation of real time traffic. It was assumed that the users may complain to the cellular operator (instead of broadband IP provider) when they experience delay or poor Mean Opinion Score (MOS) during a voice call. As in 3G case, users may wait for FTP data transfer or surfing the internet web site. In the latter case, higher latency or packet loss will not create a question from users than if the same situation experienced by users use VoIP or video services.

According to [SIMON01] and [EPITIR01], most femtocell technologies provide good quality voice calls and sufficient support to data services when the broadband IP link provides a minimum performance of:

- Less than 150 ms round-trip delay (more than 200 ms will not be practical for two ways conversation);
- Less than 40 ms jitter;
- A general packet loss of 3% or less is acceptable; however, packet loss is typically “bursty” by nature, and, as such, average rates below 0.25% should be maintained;
- At least 1 Mbps in downlink, i.e. from the broadband IP provider network to the FAP GW;
- At least 256 kbps in uplink, i.e. from the FAP GW to the broadband IP provider network.

Quality of broadband IP connection is highly depended on the following issues [EPITIR01]:

- Allocated / available bandwidth per ISP plan (Mb/s);
- Additional IP-based activities in the home;
- ISP traffic management policies (Is IPSec traffic being downgraded in the ISP networks?);
- Network load by time-of-day;
Efficiency of routing from the subscriber premises to the core network.

The allocated bandwidth per ISP can be configured based on user requirement. The maximum data rate supported varies depending on access network type. Figure 42 shows the data rate requirement of various applications and maximum data rates supported by different access network types.

If the FAP supports local IP networking and local internet connectivity, the FAP will introduce processing time and the performance of shared link used for local IP traffic and FAP-to-FAP GW traffic will be affected, especially throughput and jitter.

Traffic Management in ISP Access networks allows ISPs to offer finite service to all users during peak periods [EPITIR01]. ISPs discriminate the level of services (i.e. speed, packet loss, latency) offered to all users or a targeted group of users at a given point in time for a given application or network protocol. From an ISP perspective the advantage of shaping is that it can differentiate between time sensitive, low volume traffic flows (such as web surfing) and potentially high bandwidth downloads (peer-to-peer applications in particular). However implementing IPSec of DiffServ IP tunnelling may increase the overall traffic with some amount of overhead.

Figure 43 shows a national ISP (2 million+ subscriber) actually downgrading IPSec during peak periods of the day. As can be seen during peak period, IPSec is being downgraded in exactly the same way as Peer-to-Peer transmissions.

The change of traffic policy in ISP will have impact to the real-time VoIP application as presented in Figure 44. As it is reported in [EPITIR01], the ISP marked by a green line is a traffic managing IPSec. Consequently, the voice quality is poor to fair during peak periods of the day.

If ISPs traffic manages IPSec packets prior to deployment cellular operators can advise subscribers accordingly.

Efficiency of routing from the subscriber premises to the core network will affect overall backhaul performance. Compared to the macrocell backhaul, for FAP backhaul both user and cellular operator can not directly control the effective routing in an ISP network. IP end-to-end QoS can be enhanced if a certain SLG/SLA is introduced.
5.8.2 IP Network Service Level Guarantee (SLG)

QoS general requirement is stated in 3GPP TS 22.220 (2009-12).

“The QoS for femtocell is subject to agreement between the mobile operator and the broadband access provider, it shall be possible to request resources from the broadband IP backhaul for the QoS treatment for sessions traversing the H(e)NB subsystem.”
In order to have certain level agreement between operator and the broadband access provider, a SLG/SLA is required. The overall objective is to meet customer expectation for end-to-end QoS and reliability of IP network for all type transactions and services. SLG objectives cover:

- Performance parameters (delay, jitter, error packets, packet loss, throughput);
- Reliability: adequate (service availability) over a specific period of time including MTTR, TBF, MTTInstall, etc.;
- Priority, restoration;
- SLAs.

In terms of QoS parameters, following standards address IP QoS:

- ITU-T Rec. Y.1540 “IP Availability Performance Parameters” and Rec. Y. 1541 “Network Performance Objectives for IP Based Services”;
- 3GPP TS 23.107 concerning Quality of Service concept and architecture defining four different QoS classes namely conversational, streaming, interactive, and background;

ITU-T Rec. Y.1540 and Y. 1541 are usually referred by wire line operator while cellular operators use 3GPP QoS concept and architecture. Metro Ethernet Forum addresses QoS standard requirement for different application (given in Table 29) which are close to the one addressed in [EPITIR01].

<table>
<thead>
<tr>
<th>Traffic Type</th>
<th>Bandwidth</th>
<th>Packet loss (max)</th>
<th>Delay (max)</th>
<th>Jitter (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video conferencing (H.261)</td>
<td>100 kbps</td>
<td>1 %</td>
<td>150 ms</td>
<td>30 ms</td>
</tr>
<tr>
<td>VoIP</td>
<td>12 – 106 kbps</td>
<td>1 %</td>
<td>150 ms</td>
<td>30 ms</td>
</tr>
<tr>
<td>Streaming video (MPEG-4)</td>
<td>0.005 – 10 Mbps</td>
<td>2%</td>
<td>5000 ms</td>
<td>insensitive</td>
</tr>
<tr>
<td>Streaming audio (MP3)</td>
<td>32 – 320 kbps</td>
<td>2%</td>
<td>5000 ms</td>
<td>Insensitive</td>
</tr>
<tr>
<td>Data</td>
<td>Variable</td>
<td>Sensitive</td>
<td>insensitive</td>
<td>Insensitive</td>
</tr>
</tbody>
</table>

Table 29. Metro Ethernet Forum QoS Standard Requirement for Different Application

Backhaul femtocell should be engineered using SLG with delay, packet loss, jitter better than the required standard (QoS parameters requirement given in Table 29). IP PER (IP Packet Error Ratio) should be maintained around 10⁻⁴ and the availability can be maintained around 99.95 %. It is required that prior to FAP installation, the cellular operator should have knowledge about the performance of existing IP broadband link of the candidate users.

### 5.9 Synchronisation error models

One of the most critical aspects of OFDM-based systems is synchronization. In particular, OFDM systems are known to be particularly sensitive to frequency synchronization errors, which induce inter-symbol interference (ISI) that increases BER. Frequency synchronization errors are due to Doppler effects and frequency offset between transmitter and receiver oscillators. At the same time, time synchronization is also important, in particular in multipath fading channels. In this section, we review some synchronization error models relevant for OFDM-based systems such as femto based networks.

#### 5.9.1 Frame sync errors

The first task that an OFDM receiver must accomplish at start-up is a frame detection. In fact, frame sync error produces inter-block interference (IBI). This operation involves monitoring of the received
signal until the presence of frame is revealed. This uncertainty is modelled as a delay of the channel impulse response:

\[ h(t) = A\delta(t - t_0) \]  

(16)

where \( t_0 \) is the unknown arrival time of a symbol. Considering a multipath scenario channel (typical of indoor propagation), the equivalent baseband time-varying impulse response can be modelled, in general, as the summation of \( K \) paths, i.e.:

\[ h(t, \tau) = \sum_{k=0}^{K-1} h_k \delta(\tau - \tau_k) e^{j2\pi(f_k + \Delta f)t} \]  

(17)

where \( h_k \) is the gain coefficient for the \( k \)-th path, \( \tau_k \) is the delay time for the \( k \)-th path, the exponential \( e^{j2\pi\Delta ft} \) is due to Doppler shift

\[ f_k = \frac{v}{\lambda} \cos(\theta_k - \gamma) \]  

(18)

with \( \theta_k \) being the angle between the \( k \)-th path and the velocity vector \( v \), \( \gamma \) being the angle between the direction of the velocity vector \( v \) and the line-of-sight (LOS). The term \( e^{j2\pi\Delta ft} \) is due to frequency offset (considered in next study case). The number of paths \( K \) is, in general, a random variable. In the Rayleigh fading case, the complex amplitudes \( h_k \) are generated as independent and identically distributed complex Gaussian random variables with zero mean and unit variance.

In [YEGAMI91] Yegami and McGillen proposed a statistical factory radio channel model that is flexible enough to fit indoor data. The model may be then useful for describing the indoor channel encountered in femtocell indoor propagation. Some of the main characteristics of these models are recalled in the ensuing sections.

### 5.9.2 Number of Received Signals Estimation

A good fit to the distribution of the number of signals received in any observation interval is obtained by using the modified Beta PDF model [YEGAMI91], whose cumulative distribution is given by:

\[ F_N(x; \lambda_1, \lambda_2) = B_j(\lambda_1, \lambda_2) / B(\lambda_1, \lambda_2) \]  

(19)

where

\[ B_j(\lambda_1, \lambda_2) = \int_0^y y^{\lambda_1-1}(1-y)^{\lambda_2-1} dy, \quad B(\lambda_1, \lambda_2) = \frac{\Gamma(\lambda_1)\Gamma(\lambda_2)}{\Gamma(\lambda_1 + \lambda_2)}, \quad y = \frac{x - \mu_1}{\mu_2 - \mu_1} \]

\( \Gamma \) is the gamma function; \( \lambda_1 \) and \( \lambda_2 \) are shape parameters while \( \mu_1 \) and \( \mu_2 \) are used for scaling and shifting.

From this model, the expected value and variance of this distribution are, respectively:

\[ E(N) = \frac{\lambda_1}{\lambda_1 + \lambda_2}, \quad \sigma_N^2 = \frac{\lambda_1 \lambda_2 (\mu_2 - \mu_1)^2}{(\lambda_1 + \lambda_2)(\lambda_1 + \lambda_2 + 1)} \]  

(20)

The characteristic parameters of modified Beta PDF are shown in Table 30. They were obtained considering different indoor clutter situations, receiving threshold and link quality: Line-Of-Sight (LOS) or Obstructed (OBS).
Table 30. Values of Beta PDF parameters, for different scenarios, thresholds and links models.

<table>
<thead>
<tr>
<th>Cluster Situation</th>
<th>Threshold [dB]</th>
<th>$\mu_1$</th>
<th>$\mu_2$</th>
<th>$\lambda_1$</th>
<th>$\lambda_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>-30</td>
<td>14</td>
<td>25</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>-20</td>
<td>4</td>
<td>10</td>
<td>26</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>-10</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Heavy</td>
<td>-30</td>
<td>14</td>
<td>25</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>-20</td>
<td>4</td>
<td>10</td>
<td>26</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>-10</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Both</td>
<td>-30</td>
<td>14</td>
<td>25</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>-20</td>
<td>4</td>
<td>10</td>
<td>26</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>-10</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>8</td>
</tr>
</tbody>
</table>

5.9.3 Arrival Time and Inter-arrival Time Estimation

In [YEGAMI91] it was also proposed a statistical model for path arrival time $\tau_k$ and path inter-arrival times. For the quasi-static channel the sequence of path inter-arrival times $\{X_i = t_i - t_{i-1}, i = 1, 2, ..., N\}$ is assumed to be independent and identically distributed. Let us denote by $F_{X_i}(x_i)$ the distribution of the time between the first and the second arriving signals (paths) and by $f_{x_i}(x_i)$ the corresponding probability density function. Given the sequence $\{X_n\}_{n=1}^N$ (N number of arriving paths), the arrival times are:

$$S_0 = 0, \quad S_N = \sum_{i=1}^{N} X_i \quad N \geq 1$$ (21)

That is, $S_1 = X_1$ is the arrival time of the first signal, $S_2 = X_1 + X_2$ is the arrival time of the second signal and $S_N$ is the arrival time of the N-th signal. Assuming independent inter-arrival times, the probability density function of $S_n$ is then the convolution $f_{S_n}(x) = f_{X_1}(x) \ast f_{X_2}(x) \ast ... f_{X_n}(x)$, where $\ast$ indicates the convolution operator. The density function of $S_n$ can be computed through (1) if the density functions of path inter-arrival times are known. Some examples, fitting the indoor scenario, are given next.

**Distribution of Path Inter-arrival Times ($F_{X_i}(x)$)**

The most suitable density function that was found to model the path inter-arrival times is the Weibull probability density function [YEGAMI91] characterized by parameters $(\alpha, \beta, \nu)$. The parameters of the Weibull distributions are restricted: scale parameter $\alpha (\alpha > 0)$, shape parameter $\beta (\beta > 0)$ and location parameter $\{ -\infty < \nu < +\infty \}$. As we are dealing with positive random variables, the location parameter is 0 and the Weibull PDF becomes as follows:

$$f(x) = \begin{cases} \frac{\beta}{\alpha} \left( \frac{x}{\alpha} \right)^{\beta-1} \exp \left[ - \left( \frac{x}{\alpha} \right) ^\beta \right], & x \geq 0 \\ 0, & \text{otherwise} \end{cases} \quad (22)$$

For $\nu = 0$ and $\beta = 1$, the Weibull PDF reduces to an exponential distribution with parameter $\lambda = 1/\alpha$. The cumulative distribution function (CDF) of the Weibull distribution for $\nu = 0$, is given by:
\[ F(x) = \begin{cases} 0, & x < 0 \\ 1 - \exp \left( -\left(\frac{x}{\alpha}\right)^\beta \right), & x \geq 0 \end{cases} \]  

(23)

5.9.4 Carrier frequency sync errors

A carrier frequency offset (CFO) between the receiver and the transmitter destroys the subcarrier orthogonality producing inter-carrier interference (ICI). It is especially problematic in multi-carrier systems such as those based on OFDM. To have a negligible BER degradation, the tolerable frequency offset should be in the order of 1% of the subcarrier spacing, which is not likely to be achievable in an OFDM system without applying some frequency offset compensation technique. The Carrier Frequency Offset (CFO) can be divided into an integer part and a fractional part. Thus the frequency error can be written as: \( \Delta f = (\Gamma + \epsilon) f_s \) where \( f_s \) is the subcarrier spacing, \( \Gamma \) is an integer and \(-0.5 < \epsilon < 0.5\).

Even in the ideal case where the local oscillators are perfectly aligned, the relative speed between transmitter and receiver also generates a frequency error due to Doppler. Considering indoor propagation (according with LTE transmitting @ 2.5 GHz) and limited user mobility \( (v \approx 1 \text{ m/s}) \), the maximum Doppler shift is: \( f_d = 2v/\lambda \rightarrow 16\text{Hz} \). If we compare this value to \( 1/(NT) = F_s/N \) where \( F_s \) is sampling frequency and \( N \) is the FFT size, according to LTE standard \( (F_s/N = 1.5\text{kHz}) \), we can say that Doppler shift has no significant influence on the error frequency.

Given the multipath channel model defined as:

\[ r(t) = \sum_{k=-\infty}^{\infty} h_k s(\tau - \tau_k) e^{j2\pi(f_k + \Delta f_k)t} + n(t) \]  

(24)

the effective signal-to-noise ratio due to both additive noise and ICI is shown to be lower bounded by:

\[ SNR_e \geq \frac{SNR}{1 + 0.5947 SNR \sin^2(\pi \Delta f_k)} \left( \frac{\sin(\pi \Delta f_k)}{\pi \Delta f_k} \right)^2 \]  

(25)

where \( SNR = \frac{\sigma_s^2}{\sigma_n^2} \), \( \sigma_s^2 = E\{s(k)^2\} \) and \( \sigma_n^2 = E\{n(k)^2\} \). The difference between \( SNR \) and \( SNR_e \) has to be taken into account when considering the system sensitivity to a frequency offset \( \Delta f_k \) (fraction of the inter-carrier spacing). It is known that, in the absence of additive noise, the frequency offset must satisfy \( |\Delta f_k| \leq 1.3 \times 10^{-2} \), in order to obtain an \( SNR_e \) of 30 dB or higher (that agrees with the analysis of multiuser OFDM systems, which states that a frequency accuracy of 1-2% of the inter-carrier spacing is necessary). For \( \Delta f_k \), we may assume an uniform probability distribution in that interval.

5.10 PHY-layer abstraction

The design of PHY layer algorithms and resource allocation strategies need to be validated by system level simulations. In fact, these simulations provide an insight about the performance experienced by the user. A rigorous method to obtain system level performance consists in simulating a large number of effects like propagation models, PHY layer algorithms, MAC layer protocols and resource allocation strategies to name a few. Such approach will require very complex simulation settings and will be time consuming.
Abstraction methods have been proposed in order to alleviate the complexity of carrying out heavy simulations that take into account all layers in the same time. The principle consists in simulating MAC protocols and resource allocation strategies without simulating PHY layer algorithms whose implementation is in general more complex. The performance of the PHY layer is modelled with abstraction analytic models that provide the bit error probability or the packet loss rate depending on the channel conditions and the transmitter/receiver architecture.

For single carrier case, the PHY layer performance can be assessed analytically with closed form expressions or using interpolation on reference curves. In general, the main input for these analytic models is the signal to noise and interference ratio (SINR). It is calculated by taking into account the transmitter and the receiver architectures and also the transmit power of neighbouring transmitters. The multi-carrier case is much more complex, in fact the, performance metrics like bit error rate (BER) or block error probability (BLER) depend on SINR for all sub-carriers. This increases the number of parameters that have to be taken into account in the analytical model and even the interpolation approach become infeasible because of the large number of interpolated variables.

The main idea of most abstraction methodologies relies on deriving a new scalar parameter that replaces the vector of SINR for all sub-carriers. In a general framework, the principle can be written as:

$$\text{Performance metric} = \Phi(\Psi([\text{SINR}_1 \ldots \text{SINR}_N]))$$ (26)

Where $\psi$ is a function that transforms the vector of SINR on the $K$ subcarriers into a scalar parameter that arguments function $\Phi$. The performance metric can be the bit error probability, the block error probability etc.

Depending on the $\Phi$ and $\Psi$ functions, several abstraction methods have been proposed in the framework of 3GPP and IEEE 802.16 standardization bodies.

### 5.10.1 ESM abstraction

The principle of ESM (Effective SINR Mapping) relies on single carrier performance curves where the signal to noise and interference ratio is replaced by an average SINR. Here the average is a log average. In fact, the principle is to consider the signal to noise and interference ratio that results in the same sum capacity of a single carrier case. This can be written in the following manner:

$$\Psi(\text{SINR}_1 \ldots \text{SINR}_N) = 2^{\frac{1}{N}\sum_{i=1}^{N} \log_2(1+\text{SINR}_i)} - 1$$ (27)

where $N$ is the number of subcarriers. The value of this function is called the effective SINR. The function $\Phi$ is the reference curve of the AWGN case for the considered modulation and coding scheme.

### 5.10.2 EESM abstraction

The EESM (Exponential ESM) methodology relies also on an average SINR which is calculated as follows:

$$\Psi(\text{SINR}_1 \ldots \text{SINR}_N) = -\frac{1}{\beta} \log\left(\frac{1}{N} \sum_{i=1}^{N} \exp\left(-\frac{\text{SINR}_i}{\beta}\right)\right)$$ (28)

The coefficient $\beta$ is tuned with a reference AWGN simulation in order to guarantee the best fitting depending on the modulation and coding scheme.

### 5.10.3 RBIR abstraction

The RBIR (Received Bit Information Rate) abstraction methodology relies on the symbol mutual information rather than the effective SINR. The symbol mutual information is the mutual information that can be transmitted over an AWGN channel normalized by the modulation order. For the SISO/MISO cases, the normalized symbol mutual information is given by:
\[ SI(SINR_n, M(n)) = \log 2(M(n)) - \frac{1}{M} \sum_{m=1}^{M} E_U \left\{ \log 2(1 + \sum_{k=m}^{M(n)} \exp \left\{ -\frac{X_k - X_m + U\|U\| - |U|^2}{1/SINR_n} \right\} ) \right\} \] (29)

Where \( U \) is zero mean Gaussian with covariance \( (2 \times SINR_n)^{-1} \) and \( M(n) \) is the modulation order of the \( n \)-th sub-carrier. The RBIR is calculated from the normalized symbol mutual information of all sub-carrier as follows:

\[ RBIR = \frac{\sum_n SI(SINR_n, M(n))}{\sum_n M(n)} \] (30)

The principle of this methodology consists in assuming that the BLER depends only on the coding rate and never on the modulation order. Reference curves for AWGN setting has to be calculated for each coding rate. These curves are denoted \( \Phi_\eta(RBIR) \) (\( \eta \) is the coding rate) and the BLER is readily deduced by \( BLER = \Phi_\eta \) (calculated RBIR).

For the MIMO setting with a linear receiver, the same methodology is adopted, except that SINR is calculated at the output of the linear receiver. For MIMO case with maximum likelihood detection, the calculation of the RBIR depends on the MIMO configuration. More details can be found in the IEEE 802.16m evaluation methodology document [IEEE802.16m_EMD].

### 5.10.4 MMIB abstraction

Like the RBIR, the MMIB (Mean Mutual Information per Bit) approach relies also on the calculation of the mutual information between the source and the destination. The block error rate is calculated using and interpolated curve that depends on two parameters \( b \) and \( c \):

\[ BLER = \frac{1}{2} \left( 1 - \text{erf} \left( \frac{x - b}{c} \right) \right) \] (31)

The \( b \) and \( c \) parameters depend on antenna configuration (MIMO, SIMO, MISO), on the receiver architecture (ML, linear receiver) and on the modulation order. The values of these parameters are provided in the IEEE 802.16m evaluation methodology document [IEEE802.16m_EMD].

### 5.11 Mobility and handover

#### 5.11.1 Mobility models

##### 5.11.1.1 Outdoor movement

Three mobility models: Direct Movement (DM, also known as Multiple moving mobility model) [IEEE802.16_EMD], Probabilistic Random Walk (Waypoint) Mobility Model (PRWMM) [CAMP02] or Manhattan Mobility Model (MMM) [ETSI30.03] are utilized in simulations. The DM model reduces complexity and makes simulation more simplified. It corresponds to the movement of the user along the diresent street. This model is suitable e.g. for evaluation of a handover rate. The PRWMM model is designed for simulation of movement in a free space whereas the MMM model corresponds to the behavior of users in the downtown with regular deployment of streets.

**Direct Movement (Multiple moving mobility model)**

This model assumes all UEs moving along direct lines. The UEs are uniformly placed over the simulation area and are given a random direction and speed. The selected parameters remain in effect until a simulation drop is completed.
Each MS is assigned an angle of trajectory at the beginning of a simulation. The assigned angle is picked from an uniform distribution across the range of 0-359 degrees with resolution of one degree.

The UE remains at the selected random speed and direction for the duration of the simulation drop. When an UE crosses a wrap around boundary point within the simulation space, the UE will wrap around to the associated segment. For multiple moving mobility model, a 19-cell scenario presented in Figure 45 is used.

![Figure 45: 19-cell scenario with trajectory for multiple moving UE.](image)

**Probabilistic Random Walk (waypoint) Mobility Model**

The PRWMM utilizes a probability matrix to determine the position of a particular UE (represented by three different states for coordinate x and y) in the next instant in time (see Figure 46).

*State 0* represents the current (x or y) position of given UE, *state 1* represents the UE’s previous (x or y) position, and *state 2* represents the UE’s following position. The probability of next movement direction is described by the matrix:

$$
P = \begin{bmatrix}
P(0;0) & P(0;1) & P(0;2) \\
P(1;0) & P(1;1) & P(1;2) \\
P(2;0) & P(2;1) & P(2;2)
\end{bmatrix}
$$

(32)

Typical values set for the simulation are:

$$
P = \begin{bmatrix}
0 & 0.5 & 0.5 \\
0.2 & 0.8 & 0 \\
0.2 & 0 & 0.8
\end{bmatrix} ; \quad P = \begin{bmatrix}
0 & 0.5 & 0.5 \\
0.3 & 0.7 & 0 \\
0.3 & 0 & 0.7
\end{bmatrix}
$$

(33)
5.11.1.2 Manhattan Mobility Model

The MMM is applied to urban environments modelled as a two-dimensional rectangular grid of streets and blocks of buildings. An example of a Manhattan grid with 5 horizontal and 7 vertical streets is shown in Figure 47.

![Figure 47. Street deployment for MMM with parameterization.](image)

The MMM is based on the direct movement of an UE until it reaches a cross of two streets [ETSI30.03]. The new direction is selected at every cross. The direct movement is selected with probability $1-TP$ (usually $TP = 0.5$). The probability of turn to the right and left is the same and equals $TP/2$. This situation is depicted in Figure 48.
5.11.1.3 Indoor movement

Two different models of indoor movement are defined: house and office. The house model corresponds to the UE movement inside the family house or flat covered by one or two FAPs. The second model is more related to the conventional movement of users in the office area covered by a higher number of FAPs.

House (Apartment) movement

The FUE moves from different rooms within the house spending certain amount of time at each waypoint in the room (blue points) before moving on to another room. The speed of FUE is 1 m/s. The red points represent the places where the movement decision is taken. If the FUE gets at decision point, the next point is chosen with equal probability to all possible destinations. For instance, if the FUE can move to three different waypoints, the probability for each waypoint is 1/3. The FUE spends a certain amount of time at a waypoint at each room. The time spend by the FUE at the waypoint is described by normal distribution [CLAUS08].

Two shapes of houses are defined. The first one is a terraced house according to [CLAUS08] (Figure 49). The second type is a square shaped model of house (Figure 50).
The parameters of the distribution for determination of the time spent in the rooms and house dimensions are presented in Table 31.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution of time in room and living-room</td>
<td>Normal, $\mu=1800$, $\sigma=150$</td>
</tr>
<tr>
<td>Distribution of time in kitchen</td>
<td>Normal, $\mu=1200$, $\sigma=150$</td>
</tr>
<tr>
<td>Distribution of time in toilet and utility</td>
<td>Normal, $\mu=300$, $\sigma=22$</td>
</tr>
<tr>
<td>Distribution of time in corridor</td>
<td>Normal, $\mu=80$, $\sigma=22$</td>
</tr>
<tr>
<td>Size of terraced house</td>
<td>4 x 8 m</td>
</tr>
<tr>
<td>Size of square house</td>
<td>10 x 10 m or 15 x 15 m</td>
</tr>
</tbody>
</table>

**Table 31. Typical parameters for House/apartment movement.**

**Office building (Hotel) movement**

The movement in office/hotel is a combination of direct outdoor movement (at the corridor) and movement in the house (in the office). The model of movement is depicted in Figure 51.

If the UE leaves the personal office, then it randomly selects the destination room (other office/kitchen/bathroom/stairs/elevator) with the equal probability for all of them. If the UE enters the room, it selects the point of stay again with the equal probability. If the UE leaves the room excluding personal office, the probabilities of selection of next room is: $P(\text{personal office})=0.85$; $P(\text{other})=0.15$. If the user enter its personal office, it selects its personal point of stay with probability $P(\text{personal place})=0.9$; the probability of 0.1 corresponds to the selection of another point of stay within the personal office with the equal probability for all other points of stay.

If two (or more) floors in office/hotel are considered, all floors assume the same deployment of rooms for the sake of simplicity. The change of the floor can occur when the user is located only in the corridor at green point (elevator). The following floor is selected with an uniform distribution.
The parameters of the distribution for determination of the time spent in the offices and office dimensions are presented in Table 32.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution of time in personal office</td>
<td>Lognormal, $\mu=7.6, \sigma=0.45$</td>
</tr>
<tr>
<td>Distribution of time in other office</td>
<td>Normal, $\mu=5.2, \sigma=0.35$</td>
</tr>
<tr>
<td>Distribution of time in kitchen and bathroom</td>
<td>Normal, $\mu=300, \sigma=70$</td>
</tr>
<tr>
<td>Size of office</td>
<td>5 x 5 m</td>
</tr>
<tr>
<td>Size of floor</td>
<td>40 x 15 m</td>
</tr>
<tr>
<td>Height of floor</td>
<td>3 m</td>
</tr>
</tbody>
</table>

Table 32. Typical parameters for office/hotel movement.

5.11.2 Metrics for handover evaluation

5.11.2.1 Handover rate

Handover rate represents the overall number of handovers initiated within a time interval. This metric is used for evaluation of efficiency of the technique for the reduction of a number redundant handovers. This metric can be represented as an absolute number of handover initiations over a time interval or as an average number on handover initiations.

5.11.2.2 Handover Interruption Time

Handover interruption metric represent time interval within an UE cannot receive packets from any BS due to handover process. Handover Interruption Time is defined as a time difference between time instance $T_1$ when an UE disconnects from serving BS and time interval $T_2$ when the target BS starts with the transmission of the first packet to the UE.

$$HO_{int} = T_2 - T_1$$

The average duration of the handover interruption is defined as an average duration of the successful handovers ($N_{HO_{suc}}$).
\[ HO_{\text{AvS}} = \frac{1}{N_{\text{HO}_S}} \sum_{i=1}^{N_{\text{HO}_S}} (T_{2,i} - T_{1,i}) \] (35)

### 5.11.2.3 Data Loss

Data Loss (\(HO_{\text{DataLoss}}\)) represents the number of bits lost during the handover processes. \(D_{RX,i}\) and \(D_{TX,i}\) denote respectively the number of received bits by the UE and the number of total bits transmitted by the serving or the target BSs during the UE’s handover.

\[ HO_{\text{DataLoss}} = \frac{1}{N_{\text{HO}_S}} \sum_{i=1}^{N_{\text{HO}_S}} (D_{TX,i} - D_{RX,i}) \] (36)

### 5.11.2.4 Handover Failure Rate

Handover failure rate (\(HFR\)) represents the ratio between failed handovers (\(N_{\text{HO}_\text{fail}}\)) and total handover attempts (\(N_{\text{HO}}\)).

\[ HFR = \frac{N_{\text{HO}_\text{fail}}}{N_{\text{HO}}} \] (37)

### 5.11.2.5 MAC management overhead caused by handover

This metrics presents an amount of overhead generated in uplink and in downlink during one handover procedure and is denoted as \(HO_{OH}\) (see equation (38)). It consists of all MAC messages transmitted related to the handover process. \(MMO_{UL}\) represents MAC management overhead caused in uplink and \(MMO_{DL}\) represents MAC management overhead caused in downlink. \(N_{MM_{UL}}\) and \(N_{MM_{DL}}\) is a number of MAC messages sent in uplink and downlink respectively.

\[ HO_{OH} = \sum_{N_{MM_{UL}}} MMO_{UL} + \sum_{N_{MM_{DL}}} MMO_{DL} \] (38)
6 BUSINESS MODELS

This section describes the business model and perspectives in the case of deploying femtocells. The market that we highlight in this section is corporate customer market in urban/dense urban. The detailed analysis and business case of the scenarios will then be analysed in the next assignment within WP2 (Deliverable D2.3, Market opportunity, business model and technology implementation-dissemination plan). All analysis provided in this section will be provided in high level while more detailed and comprehensive report will only be addressed in the D2.3 deliverable. This section also will focus specifically on Indonesia market, but in some cases will also give the portrait of global data.

Various business cases of femtocell have been addressed in several publications especially from Femto Forum. However we only see the implementation of femtocell considering the residential market and for the developed countries, especially Europe. We believe that residential market characteristic of one country or region is different from other country/region, especially between developed and developing country. In developed country, most people live in apartment or a house with more than two stories that may have coverage and quality problems. This situation may be different with developing country where most people live in a house with one storey, so the problem of coverage and quality of mobile services is definitively less relevant. In addition, the study of business case for corporate customer is quite few and we see that the implementation of femtocell for corporate customer can be a common interest for developed and developing countries.

We choose Indonesia market as the market to cover based on the opportunity of the market size that can be served and Indonesia is one of the emerging market in Asia that still grow significantly within the next 5 years. The operator to be chosen is the leading mobile operator in Indonesia market, TELKOMSEL that is currently serves up to 51% of the market. TELKOMSEL is also the subsidiary of PT TELEKOMUNIKASI INDONESIA (TELKOM) the biggest fixed operator and leading telecommunication operator in Indonesia.

The selection of the market in terms of deploying the femtocell is based on the assumption that the corporate customer market in urban/dense urban has more potential than other two scenarios stated in section 2. This assumption is based on limited availability of backhaul in the residential and remote area especially in Indonesia, the buying power of the market and the competition level that push the mobile operators in Indonesia to capture more subscribers.

6.1 Telecommunication industry

The global telecommunication industry will reach 1.1 trillion Euros in the year of 2010\(^4\). In some regions -Western Europe, North America and some countries in Asia Pacific region- the industry is maturing with growth rate less than 5%. But in some emerging countries like China and India, Indonesia and Philipina, the telecommunication industry is still growing significantly above 10% growth rate. Western Europe has the biggest market share of whole global telecommunication market. It contributes up to 25% of the global market, following by North America with 23% in 2010. Asia Pacific contributes about 17% of the global market in 2010.

The emergence of mobile technology, internet services and huge content has changed the market behavior in searching and communicating with others. Mobile terminals (cellular phone, laptop/netbook, MID) has become a primary need and part of market life style. Most services are run and consumed through the mobile terminals and the need and usage of fixed telephony has decreased significantly. That is why telecommunication market now is dominated by mobile users, it contributes up to 56% of the global market. Fixed voice is projected to contribute about 30% of the total market but its growth rate has been decreased since the last three years. Mobile and data/broadband services growth rate are still relatively high at 7% and 12% respectively within 5 years (2005-2010).

\(^4\) In this section some data about currency has been converted to Euro unit, with assumption 1 € = 1.19 USD = 11,632 Rp
Indonesia’s telecom sector is experiencing growth that is by any measure exceptional. The market dynamics create for a highly competitive industry in which the consumers are reaping the benefits. Whereas penetration rates indicate mobile phone penetration is close to 70% of the population, realistic penetration factoring in the number of mobile phone users with multiple handsets would adjust down that number closer to 50%. The democratisation that is occurring in the market has set up the Indonesian market to see dramatic rises in mobile phone usage over the next three to five years. The competitive landscape coupled with the ever increasing capabilities of mobile phones is priming Indonesia for a major societal change as more Indonesians are becoming mobile phone users. The Indonesia telecommunication market size is projected up to Euro 9.59 billion in 2010, grows about 14.5% compared to 2008. The subscriber is projected up to 206.2 million in 2010 and grows about 36% compared to 2008 (see Table 33).

<table>
<thead>
<tr>
<th>Indonesia Telco Industry</th>
<th>2008</th>
<th>2009E</th>
<th>2010P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue (Euro Bn)</td>
<td>8.37</td>
<td>8.62</td>
<td>9.59</td>
</tr>
<tr>
<td>Subs (000)</td>
<td>150,861</td>
<td>171,777</td>
<td>206,245</td>
</tr>
</tbody>
</table>

Table 33. Mobile operators in Indonesia (source: TELKOM Indonesia)

6.1.1 Mobile business and market

According to DITTBERNER’s in 3Q2008 global mobile subscriber surpassed 3.6 billion active subscribers (source: 3Q08 Global Telecom Subscriber Survey, Dittberner), however the mobile wireless subscriber growth continued to slow in 3Q08 with QoQ growth of only 4%. This is because in some regions, the mobile market is already near saturation in penetration (more than 100% penetration), especially in Western Europe. About 17% of operators saw a decline in active mobile subscribers in the third quarter. These are located mostly in Western Europe where many markets have approached or even exceeded 100% penetration per capita.

The operators showing the strongest growth are operators in developing markets and they are mostly in Asia region. Asia is still the biggest market share in mobile subscriber in the world. Not surprisingly, because 56% of the world’s population reside in Asia region and the penetration rate of telecommunication users is growing tremendously recently. For some developed countries in Asia
(Singapore, Malaysia, Japan), the wireless penetration is already more than 100%, but for some developing countries (Indonesia, India, China), the penetration is still growing.

Due to the growth of mobile data, many mobile operators already serve the market with 3G services. However the 3G market is still concentrated in the mature, more affluent markets of the world. 3G is following the same development path as fixed broadband did. About 42% of this 3G market share is in Asia and the market is still growing.

However, most wireless operators in the world right now have a negative ARPU growth in 2nd quarter of 2009 as shown in figure 50 below. India and Indonesia, compared to their other South Asia counterparts are of the worst hit with -25% and -15% ARPU growth respectively (see Figure 53).

![Figure 53. Mobile subscriber market share (source: 3Q08 Global Telecom Subscriber Survey, Dittberner)](image)

For Indonesia, with about 237 million population, in 2009 the wireless penetration estimated about 72% and projected for 87% in 2010. The wireless industry in Indonesia is divided in two big industry; fixed industry and mobile industry (see Figure 54).

The Indonesia mobile business is segmented in two models; the full mobility business and limited mobility business. The limited mobility segment (called FWA-Fixed Wireless Access) use CDMA technology platform and right now there are 4 operators serve the market in Indonesia. While the full mobility (called cellular) mostly operators use GSM technology platform. Today there are 8 cellular
operators in Indonesia, 5 operators use GSM technology and three operators (Mobile-8, SAMPOERNA and SMART) use CDMA technology platform for theirs cellular business (Table 34).

<table>
<thead>
<tr>
<th>TECHNOLOGY/LICENCE</th>
<th>OPERATOR</th>
<th>COST BASED (Thousand)</th>
<th>MARKET SHARE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIXED</td>
<td>FWL</td>
<td>TELKOM</td>
<td>8,706</td>
</tr>
<tr>
<td></td>
<td>TELKOM-Flexi</td>
<td>14,886</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>BAKRIE-Esia</td>
<td>10,128</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>ISAT-StarOne</td>
<td>543</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>MOBILE-8</td>
<td>3,493</td>
<td>2% 2%</td>
</tr>
<tr>
<td></td>
<td>SAMPOERNA</td>
<td>796</td>
<td>0% 1%</td>
</tr>
<tr>
<td></td>
<td>SMART</td>
<td>3,263</td>
<td>2% 2%</td>
</tr>
<tr>
<td></td>
<td>TELKOMSEL</td>
<td>79,774</td>
<td>44% 51%</td>
</tr>
<tr>
<td></td>
<td>INDOSAT</td>
<td>28,700</td>
<td>16% 18%</td>
</tr>
<tr>
<td></td>
<td>EXELCOMINDO</td>
<td>26,647</td>
<td>15% 17%</td>
</tr>
<tr>
<td>WIRELESS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDMA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MOBILE-8</td>
<td>3,493</td>
<td>2% 2%</td>
</tr>
<tr>
<td></td>
<td>SAMPOERNA</td>
<td>796</td>
<td>0% 1%</td>
</tr>
<tr>
<td></td>
<td>SMART</td>
<td>3,263</td>
<td>2% 2%</td>
</tr>
<tr>
<td>GSM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FULL MOBILITY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Cellular)</td>
<td>TELKOMSEL</td>
<td>79,774</td>
<td>44% 51%</td>
</tr>
<tr>
<td></td>
<td>INDOSAT</td>
<td>28,700</td>
<td>16% 18%</td>
</tr>
<tr>
<td></td>
<td>EXELCOMINDO</td>
<td>26,647</td>
<td>15% 17%</td>
</tr>
<tr>
<td></td>
<td>HUTCHINSON</td>
<td>7,082</td>
<td>4% 5%</td>
</tr>
<tr>
<td></td>
<td>NTS</td>
<td>5,502</td>
<td>3% 4%</td>
</tr>
</tbody>
</table>

Table 34. Mobile operators in Indonesia

During the last 7 years, Indonesia wireless market grew tremendously. The cellular market grew with CAGR 40.51% (2003-2009) from 20.1 million subscribers in 2003 to 154 million subscribers in September 2009. The presence of FWA services in Indonesia market has changed the competition environment in mobile business. FWA market itself has grown with higher CAGR (2003-2009: 96.2%) than cellular market. It grew from 0.3 million subscribers in 2003 to 34.2 million subscribers in September 2009. The subscriber of FWA and cellular in Indonesia are dominated with prepaid subscriber (97%) rather than postpaid subscriber (Figure 55).

Due to the tight competition in this industry, all operators promote heavily in the market to increase their customer base number. This situation has brought all operators in to the price war and from the most expensive since 2008 the telecommunication price in Indonesia becomes the cheapest in the world.

![Figure 55. Indonesia mobile market (source: TELKOM)](image-url)
Indonesian wireless sector remain strong, and conducive for organic revenue growth, as effective penetration remains relatively low. Analyst forecasts revenue growth of ~10% for the rated Indonesian telco market. This will be driven by deepening market penetration, ARPU stabilization, a continued increase in minutes of usage, and anticipated increased penetration for mobile broadband applications.

The ARPU of cellular market in Indonesia is also falling like other market in many regions, with a decline of 24% in 2008 and 13% in 2009. The ARPU is about Euro 4.30 in 3rd quarter of 2008 and decrease to Euro 3.61 in 3rd quarter of 2009. But the minutes of usage (MOU) of the cellular is increasing steadily, from about 160 minutes of usage per customer in 3rd quarter of 2008 to 200 minutes in the 3rd quarter of 2009 (see Figure 56).

Operators have moderated their strategy of selling SIM cards with promotional rates, free talk time and free SMSs, and have given incentives to subscribers to buy more minutes at a higher price. In some cases, operators have cautiously increased tariffs and reduced the number of free minutes in an effort to monetize the overall higher minutes of usage.

![Figure 56. ARPU vs MOU of cellular in Indonesia](image)

The marketing and promotional cost of operator in Indonesia is varying from 5% to 10% of its operating expenses. Of course the contribution of the cost depends on the strategy of each operators. For TELKOM, as the biggest cellular operator in Indonesia, in 2009 it had about Euro 3,611 million and about 5% (Euro 198 million) was allocated for its marketing cost.

### 6.1.2 Broadband business and market

The broadband business and market has grown significantly since the internet network offer huge contents to the users. In 2008, the number of internet users in the world is about 1.6 billion users. Most of the users are from Asia Pacific (45%) and Europe (22%). China as one of the most populated country in the world, in 2009 has 384 million of internet’s users (source: www.internetworldstats.com), but the most internet-penetrated countries in the world are Norway, Sweden, Finland, Netherlands and United States (see Figure 57).
Asia right now is becoming the focus of broadband growth in the world, especially India and Indonesia with growth rate more than 40%. The number of broadband subscriber is projected about 828 million in the year of 2013 with CAGR (2008-2013) up to 14%. In some regions, especially developed market, like North America and Europe, the growth rate of the broadband users is slowly (below 10%) due to the near saturation in market.

That is why the broadband service providers in developed and developing markets face different strategic challenges. In developed markets, broadband service providers improve the reach and profitability of existing low/mid-speed broadband and develop new methods of monetising the network through wholesale options, value-added services and better segmentation. They also deploy next-generation very high-speed broadband and build business models and services to support this investment.

While in the developing markets, the broadband service provider continues the steady roll-out of broadband networks and increase penetration in consumer and enterprise markets.
The global broadband access market has grown from fewer than 10 million lines in 1999, to more than half a billion at the end of 2009, predominantly through the growth of DSL-based solutions, as well as cable and other technologies. Although growth has started to slow down in percentage terms, there remains significant scope for more homes and businesses to connect, especially in developing economies, such as China. Older fixed broadband services in more industrialised economies will gradually be replaced with fiber.

The other major area of change is in wireless. Since 2007, the rapid access will grow has been growing faster than fixed connections, reaching more than one billion active individual users and almost two billion devices by 2020. Although a strong fixed/mobile overlap will remain, there will also be a growing group of users whose only broadband access is via 3G, 4G or similar technologies.

For the fixed and mobile broadband penetration, Europe has the biggest penetration in the world (fixed: 25%, mobile: 45%) then follow by South East Asia and North America.

For Indonesia, the growth rate of broadband Indonesia projected up to 49%, but the penetration rate is estimated the lowest in Asia. In this broadband business the majority market (67%) is served by TELKOM Group with its Telkom xDSL and Telkomsel mobile broadband.

Majority of broadband revenue in Indonesia comes from the access network (80%) but the contribution of content and value added service is growing. The size of the broadband market (in term of revenue) in 2010 is projected up to Euro 1.35 billion and it produces from the ARPU of Euro 14.9. But the ARPU will tend to decrease in the next 3 years while the revenue will increase (see Figure 60).
The competition in the broadband business (xDSL, cable and mobile broadband) has reduced the tariff significantly and this situation will push the subscriber number up to 11.8 million subscribers in 2013. Most of the broadband subscribers are small to medium company, executives and professional.

For the mobile broadband, the competition is very tight and this simply can be seen through the various offering of the services to the market. And this attractive marketing has increased the number of the mobile subscribers (see Figure 61). For mobile broadband, Telkomsel is the leading in the market share, it has 36% market share with 127,437 subscribers in 2008. It is estimated that in the 1st quarter of 2010, the number has reached 25 million users. The attractive offering (with bundling) and various product package (daily, weekly & monthly subscription) has increased the subscriber growth significantly (see Figure 62).
6.1.3 Telecommunication regulation in Indonesia

Regulation may involve the implementation of femtocell regarding the mobile spectrum use, the use of other’s party network (eq. backhauling) especially for mobile operator only that requires backhaul network from fixed operator, the qualified technicians to install the femtocell access point in the customers site and also the femtocell registration.

Femtocell will use the spectrum of the mobile operator. In this case, regulatory bodies must involve in managing the use of the spectrum, so the Regulator can assure the end-user will receive a good quality of service from the operator.

In case of Indonesia, the telecommunication industry is regulated by “Information and Communication Ministry”. This regulatory body gives a licence to cellular service providers and internet services providers. The frequency spectrum allocation in Indonesia is allocated as Figure 63 below.

Figure 63. Indonesia frequency spectrum allocation (source: TELKOM Indonesia)
In terms of the use of other’s party network for femtocell backhauling, as traffic needs to be backhauled through the end-users’ broadband access line, fixed-service providers will see a significant increase in traffic on their networks. In the case of an integrated service provider, the femtocell would be connected to their own fixed broadband access, so it should not pose a problem. But for a purely mobile carrier, the end-user would have to connect the femtocell CPE through a third party broadband provider. This broadband provider will then have to deal with a significant data traffic increase on its network without obtaining any related benefits. Many networks are already stating their unwillingness to carry such traffic without additional remuneration, either from the mobile operator (B2B: Business to Business) or the end user (B2C: Business to Consumer).

Regulatory bodies may have to make a ruling on this aspect to ensure that:

a) Fixed broadband suppliers will not block the access to their networks for traffic coming from femtocells CPE.
b) Purely mobile players will not use third party broadband access free of charge.

In the case of femtocell registration, regulatory needs to consider carefully whether service providers need to obtain an authorization to install every single femtocell. For every authorization, service providers are facing heavy and costly process while deploying femtocell networks. In Italy, if femtocells are owned by the operator, the service providers need to obtain an authorization to install every single femtocell.

For Indonesia market, the use of femtocell will help the mobile operator to improve their indoor quality (office and home). There is only one integrated operator in Indonesia, TELKOM, that can utilize its own network resources (fixed broadband and mobile) to deploy the femtocell. This situation will be a competitive advantage to TELKOM. The other mobile operators need to deal with other third party as fixed broadband service providers to enable mobile traffic backhauling.

6.2 Femtocell value & ecosystem

6.2.1 Femtocell values & drivers for users

Values of the femtocells adoption by end users are:

a) Indoor Coverage
   The main driver users could perceive in the femtocell solution is achieving better indoor coverage. But as this is supposed the operator or service provider responsibility, users (consumers or enterprises) may not be willing to pay for having better coverage.

b) Quality of Service
   The main driver for femtocell rollout is the increased quality of service (voice and data) for in-building usage, but CPEs should be considered by operators (bundling).

c) Femtozone Tariff
   Operators offer femtocell access for in-house or in-office usage should be able to offer attractive tariffs that ensure the lower total cost of their usage within the femtozone. Lower tariffs would be perceived by the end users as a good reason to adopt a femtocell CPE.

d) Alternative to a 2nd computer
   Consumer would see the value of having a femtocell as it would allow them to use their mobile phone as an alternative to a second computer. Rather than buying a second or a third computer to allow several users to access the internet at home or office, they could use their handsets.
Unlimited data services
Operators are likely to offer data services on femtocells which have far higher usage limits or are even uncapped, enabling users to use these services without fear of the associated charges. This will also encourage users to use such services for the first time, overcoming initial barriers to access and ultimately to adopt these services beyond the home as well.

Compelling new femtozone services
As well as delivering existing mobile network services better and at more attractive prices, femtocells can also deliver brand new services, which use the specific knowledge of the user’s location to offer extra benefits such as control of devices around the home, synchronisation of content to and from the mobile device and fast, high-quality access to data stored on other devices on the home network such as media servers.

6.2.2 Femtocell values & challenges for operators
The values of the femtocells adoption by operators are:

a) Revenue Impact
Femtocells deliver new revenue streams from value-added services and by increasing mobile usage, both within the femtozone and on the wider network, as users demand services they have first experienced on the femtocell.

Location-specific tariffs such as ‘homezone’ tariffs defined by the coverage area of a few macrocells may extend over a large area potentially comprising the whole of a small town and therefore lead to revenue leakage. This decreases operator revenues without decreasing the associated costs. Location-specific tariffs delivered via femtocells are precisely targeted and reduce the costs of delivery, thereby increasing the overall value to the operator.

Family and group contracts, which increase the loyalty of the femtocell users to the operator, extending both the value and lifetime of the contract. The attractiveness of such contracts is also increased by the ability to offer service bundles including entertainment services, which are typically bought by the whole family rather than by a single individual.

Differentiated services, encouraging users to adopt services from operators offering femtocells over those available from other operators.

b) Cost Savings
Femtocells enable operators to defer and reduce the cost of macrocell roll-out to deliver enhanced indoor coverage and network capacity.

Femtocells produce operational savings—especially on the major items associated with sites in power, backhaul and site rental.

By reducing the likelihood of customer churn between operators, femtocells reduce the cost of customer retention.

c) Time to market
Femtocells allow rapid, low-risk, focused deployment of next-generation technologies such as LTE and WiMAX, avoiding the extended time scales and cost needed to secure site rights and construction resources to permit macrocell upgrades.

New services can be rapidly provisioned to relevant users and locations, enabling them to be trialled and optimised for wider roll-out more quickly and with lower risk, enabling Internet-style speeds of new service introduction.

On the other hand, the challenges for operators to achieve the potential value in femtocell adoption are:
a) Market challenge
This is about public awareness, public concerns regarding the services, tariffs and alleged health issues, the support for a wide range of use cases and the business case.

b) Radio and physical challenges
   The challenges of interference management between femto and macrocells, radio resource and mobility management, implementation issues (e.g. synchronisation, signal processing and cost).

c) Network challenges
   The architectures and interfaces, management and provisioning, scalability and security.

d) Regulatory challenges
   The regulatory benefits, spectrum issues, and service issues.

6.2.3 Femtocell strategic objectives to operators

6.2.3.1 Mobile operator
   It would be worthwhile for Mobile Only Service Providers to deploy femtocells solutions for 3 main reasons:
   1) First, they would be able to compete with Integrated and land line service providers offering comparatively attractive rates for mobile usage at home. This would be particularly the case in the US market where end-users do not avail of high quality indoor coverage.
   2) Second, they would enhance their indoor coverage and reduce migration of voice and data calls from their networks to landline provider competitors.
   3) Third, they would be able to redirect their traffic and backhauling onto fixed broadband access service networks.

6.2.3.2 Fixed operator
   Fixed only service providers would have many good reasons to provide their end-users with femtocells solutions as it would allow them to capture the traffic which normally goes through their mobile competitors' network and charge the users when they access their network at home with their mobile devices.

   Unfortunately, purely fixed players do not have the right to use mobile spectrum, so they cannot offer such services and need to stick to standard FMC solutions with dual mode handsets using either bluetooth or WiFi terminals.

6.2.3.3 Integrated operator
   Integrated Service Providers would have the most to gain from offering femtocells solutions:
   1) To improve their indoor network coverage.
   2) To offer packaged Quadruple Play services including fixed telephony, Internet Access, IPTV and Mobile telephony at very competitive rates.
   3) To offer family plans with special rates while using mobile phones at home. This would help integrated service providers to secure a whole household as a customer for fixed and mobile services.
   4) To leverage their fixed broadband subscriber base by selling them mobile services. On the another hand, they would also be able to leverage their mobile subscriber base by selling them fixed broadband access to use their mobile phone at better rates while connecting from home.
   5) To offer free of charge, or at low cost, mobile data at home to increase mobile browsing and data service adoption, driving outdoor customer behaviour and ARPU growth.
6.2.4 Femtocell substitution solutions

There are four main alternatives solutions threatening femtocells: FMS (Fixed-Mobile Substitution) offers based on Home Zone tariffs, FMC (Fixed-Mobile Convergence) solutions based on UMA technology (Unlicensed Mobile Access) and equipments such as picocells and repeaters.

a) Fixed-Mobile Substitution offers

A homezone generally covers a zone (within a radius of 500 m to 2 km) surrounding a location chosen by the user. This is generally (but not necessarily) the user’s home, where calls from mobiles to fixed numbers are available at beneficial rates, i.e. competitive in relation to charges for fixed-fixed calls. Outside this zone, calls to fixed numbers are charged at the same rates as mobile calls. In the case of calls to mobiles, on the other hand, the homezone has no influence. Obviously femtocells allow for the creation of much smaller homezones, thus avoiding revenue leakage and maximising value for the carrier. In addition, in terms of indoor signal quality, femtocells are better than the macrocell on which the homezone tariffs are based. Femtocells allow operators to cut the cost of backhaul and power and this means they can offer very attractive tariffs unlike with FMS solutions. The operators could also provide interesting data offers such as mobile internet services.

b) Fixed-Mobile Convergences solutions

The other threat to femtocells are FMC solutions based on UMA, which could slow down their adoption, the Unik Orange plan, for instance, enables its subscribers at home or at any Orange WiFi access point to make free calls to fixed phones in France. However, these solutions require dual-mode devices, particularly given the evidence suggesting that increasing numbers of consumers prefer to use their mobile handset wherever possible. Other FMC drawbacks are the poor autonomy of WiFi based handsets and the low voice quality; indeed, WiFi and particularly Bluetooth were not designed to provide high service quality. In addition, the proprietary box for the femtocell (unlike the readily interchangeable Wi-Fi access points) helps to “lock in” the customers. With this system, the user will not have access to a Wi-Fi terminal. The dissatisfaction risk is thereby minimised. Lastly, the danger of open hotspot usage cannibalising mobile voice traffic outside becomes nil.

c) Picocells

In the Enterprise market, picocells may represent a threat to femtocells adoption because they allow more simultaneously users calls which is relevant for an enterprise usage while with a femtocell current designs enable around 4 simultaneously users calls. However, the cost of picocells is higher than for femtocells particularly the cost of maintenance and installation which have to be done by the operator.

d) Repeaters

As an alternative solution for improving the indoor coverage, service providers may consider deploying the signal repeaters. Operators such as Vodafone are in the process of trying out the technology. This solution, however, does not overcome the capacity issue. In addition, the repeaters regulations may change in some markets, creating more barriers for the deployment.

6.2.5 Femtocell ecosystem/value chain

The femtocell ecosystem and value chain is made up of 3 main players. It includes Equipment Vendors, Service Providers and End-users. All three players add value to the femtocell ecosystem by leveraging either their expertise in the area, or their needs in terms of services.

Equipment Vendors supply the Service Providers with the suitable equipment to allow them to offer relevant services which meet End-users needs.

In addition, standardisation bodies and consortium play a key role in the emergence of the technology.
There are three categories of femtocell Equipment vendors, which are specialised in different types of equipment i.e. CPE, chips and controllers.

Service Providers or operators today are already heavily involved into the femtocell ecosystem either through trials or commercial deployments. All categories of Service Providers are getting in on the act, from Fixed Service Providers to Mobile players on through to integrated Operators.

Fixed service providers or operators are not deploying femtocell solutions as the regulation does not authorise them to market spectrum capacity (licence issue), but they have a central position in the femtocell value chain as the traffic eventually transits through their broadband access network (xDSL).

Mobile Service Providers are the one who aim to maximise their network coverage and to push added value solution usage.

While integrated service providers who offering both fixed and wireless broadband access are at the forefront of the market. Some operators have deployed commercial femtocell solutions to support an aggressive customer acquisition and retention strategy like Softbank in Japan. Worldwide, integrated operators such as T-Mobile in Germany, NTT DoCoMo in Japan, Orange in France, ChungHwa Telecom in Taiwan or Maxis in Malaysia, are all conducting femtocells trials.

Though not decision-makers at the early stages of the technology’s development, end-users are part of the femtocell ecosystem. We can distinguish 2 user categories: consumers and businesses. In both cases, acquiring a femtocell will be motivated by better indoor coverage requirements linked to mobile network access. The difference is in the value each segment will attribute to the service. Firms may need and expect more from the related services.

6.3 Femtocell market analysis: a case for corporate customer

In this business model case, the market will only consider for corporate customer in urban/dense urban in Indonesia. Urban areas are characterized by a high population density, typically more than 1000 persons per square kilometre. These areas have the highest density of potential customers and higher competition. Therefore, in these areas the operators should plan coverage based on small cell size (high density customers). It is usually very difficult to reach a high customer penetration because there are usually many operators offering a high variety of services.

Main characteristics of urban scenario are:

- Highest density of potential broadband customers
- Many multiple tenant office and residential buildings
- Smaller cell sizes to meet capacity requirements
- Strong competition: Drive by market size and availability of alternate access technologies
- Due to the competitive environment a new operator can expect: lower market penetration and higher marketing and sales expense
- Licensed spectrum would be desirable to minimize potential for interference

6.3.1 Indonesia corporate customer market

Indonesia corporate customer market will still grow significantly within 2009-2014 with CAGR about 13% and projected to Euro 5,889 million in 2014. Some key drivers of this growth are:
- The stabilization and growth of Indonesia economic (2009 GDP: 5.5%) make investors and companies expand their business
- The increase of ICT outsourcing trend in Indonesia
- Service providers extensively expand their infrastructure and services for corporate customers with competitive price to capture more market.

The corporate customer market in Indonesia can be categorized in 6 main segments:
- Government
- Mining & construction
- Manufacturing
- Trade & industrial park,
- Trading & service
- Finance & banking

The top-3 biggest market segments are Trading and Service, Finance and Banking and Government. In term of growth rate, the top-3 segments are Trade and Industrial Park, Trading and Service, and Finance and Banking. These market segments are spreading in all regions in Indonesia and the potential regions for corporate customer segment are Java and Sumatra (see Figure 65).

Figure 65. Entreprise market segmentation and potential in Indonesia (source: TELKOM)

6.3.2 Enterprise Services and Trends

Enterprise customer has unique characteristics, which will challenge all providers (networks, services, software, devices, etc) to meet the requirements. The uniqueness are derived not only from the
different type of company: even if some companies belong to the same type of enterprise (e.g., banking), each company will have different requirements. This is the main reasons why the providers provide customized services and solutions.

Services and solutions provided to a customer, traditionally fulfilled using managed networks solutions, which comprises of customer premises equipment (CPE), access network (can be xDSL, FTTx, WiMAX, etc.), until the transport network if needed. The Quality of Services (QoS) of managed network services is the key parameters that can be customized by the provider for each customer (see Figure 66).

Figure 66. Illustration of typical enterprise solutions (source: TELKOM Indonesia)

In order to provide the solution for enterprise customer, TELKOM had already used the solution framework for enterprise which consist of layered of solution which start from Access and Connectivity towards IT Services and Outsourcing, as stated in [TELKOM]. Each layer will support services and solution and the lower layer services will support the upper layer services. Figure 67 illustrates the typical solution framework.

TELKOM already planned the prospective generic solutions for each enterprise customer segments in 2010. Some of prospective solutions are:

a. Finance and Banking Solutions
   - InsureNet: Insurance Shared Service Platform
b. Government Solutions
   - Indonesian Government Network: to integrate all Government Networks and e-Government Applications
   - Public Service Solution: integrated public service networks and applications, which provide multiple ways of interaction with citizen (i.e. web, cell phones, call center and traditional channel via front desk)
c. Plantation Solution:
   - Intelligent Plantation Solutions: suites of hardware, software and sensors for environmental monitoring at estates (monitor temperature, humidity, light, soil condition)
d. Trading and Services Solution:
- E-Education Content and Applications: Centralized application platform with consolidated central Education database. Central database allows integration of information across schools/offices, ensuring data portability and integrity.

Figure 67. Illustration of prospective enterprise solutions in 2010 (source: TELKOM)

6.4 Femtocell business model for mobile operator

In this first business model analysis, the market will only consider for corporate customer in urban/dense urban in specific region of Indonesia. This section also only considers the business model for mobile operator and describes the rationale of how an organization creates, delivers, and captures value through femtocell. The financial projection and model will not cover in this first business model analysis. All the financial projection and model of the three scenarios of the business case will be compared and analysed in deliverable 2.3 of FREEDOM.

6.4.1 Coverage assumptions

Indonesia is an islands country spreaded in wide area. But the market is concentrated in Java island region. As the business and government activities are centered in Jakarta, most of the business office’s headquarters are located in Java especially Jakarta city.

This condition creates many chances for femtocell which could accommodate any kind of user communication and collaboration within the company, even for user who are traveling and working in remote location. Service provider could offer value added service over femtocell by identifying and registering all the femtocell access point in one company’s cloud.
In considering that most of the business headquarter offices are present in Jakarta, implementation of femtocell in this section will be focused in Jakarta business districts. As stated in Section 2.1 of this document, we found that business users have difficulties in achieving good quality of their mobile services especially in during office hours. The number of population in Jakarta area (March 2010) is about 8,522,589 (source: http://www.kependudukancapil.go.id). This number almost double during office hours, where people staying around Jakarta (satellite cities) go to their offices.

The potential area for femtocell implementation in Jakarta can be divided in 4 (four) business districts; the center of Jakarta, East Jakarta, South Jakarta and Northwest Jakarta. Focused implementation is necessary for initiation state in order to develop effortless evaluation process and minimise cost of investment. As of today, operators are pushing femtocell solutions on a small scale. Service Providers will push the solution on a mass market scale if femtocells are deemed to give significant competitive advantage in terms of integrated offering and if return on investment is high enough.

6.4.2 Market assumptions

There are about 31,000 corporations (small, medium and big) in Jakarta. The big corporate or high end market is about 20% or around 6,200 companies. These companies usually use more than one service provider to support their telecommunication and IT system. The average number of employee for this segment is about 500 employees and most of all the employees have mobile phone.

TELKOM as the biggest and leading operator in Indonesia has the biggest market share (42%) in this market segment and right now TELKOM manages around 6,000 corporate customers. This number will then be used to project the market for Jakarta region. Based on telecommunication expenditure, corporate customers can be divided in to three clusters; Cluster-1 spend above Euro 43,000, Cluster-2 spend Euro 8,500-43,000 while Cluster-3 spend Euro 4,300 to 8,500.
As mentioned in Sec 6.2.3 in this document, the Femtocell will help mobile operator to build their competitive advantage in offering a good quality of service so they can lock-in their customers, reduce the customer churn and acquire more customers.

In this market assumption scenario, we assume that Femtocell’s operator can penetrate their customers to use Femtocell up to 80% in the Year-5, that is about 4,800 corporate customers. As the average number of employee per company is about 500 employees, and we assume only 80% of the employee can have access to the femtocell service (Femtocell based CPE availability, Key employee in the company), so the Femtocell’s operator in this scenario can serve up to 1.9 million end-users.

<table>
<thead>
<tr>
<th>Coverage: Jakarta Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population (March 2009)</td>
</tr>
<tr>
<td>Number of Big Companies (HEM-High End Market)</td>
</tr>
<tr>
<td>Average Employee @company</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Market Assumptions</th>
<th>Year-1</th>
<th>Year-2</th>
<th>Year-3</th>
<th>Year-4</th>
<th>Year-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femto’s Operator Customers Penetration (%) (based on TELKOM’s Corporate Customers)</td>
<td>10%</td>
<td>25%</td>
<td>50%</td>
<td>70%</td>
<td>80%</td>
</tr>
<tr>
<td>Femto’s Operator Corporate Customers</td>
<td>600</td>
<td>1,500</td>
<td>3,000</td>
<td>4,200</td>
<td>4,800</td>
</tr>
<tr>
<td>Number of Femtocell’s end-users (assumption: 80%)</td>
<td>240,000</td>
<td>600,000</td>
<td>1,200,000</td>
<td>1,680,000</td>
<td>1,920,000</td>
</tr>
</tbody>
</table>

Table 35. Market assumptions

6.4.3 Revenue stream model assumptions

Here are some revenue models that can be implemented by femtocell’s service providers (mobile operator) to achieve their business strategic objectives through corporate customer:

- Corporate Customers pay for their Femtocell CPEs

In the US, where the added value of the Femtocell solution is clearly linked to indoor coverage capacity, end users are willing to pay for a femtocell solution to obtain better in-building connectivity. Therefore, American operator strategy is to make the customer pay an upfront fee to acquire the femtocell CPE and then possibly a subscription fee.

Verizon charges USD 250 for its femtocell CPE and does not require its customers to pay for usage. Sprint Customers must acquire a femtocell CPE which costs $100 to access dedicated services

- Femtocell Flat Fee

This is one of the strategies to foster take up of femtocells solution for customers. Some providers actually already offer this pricing strategy to their market.

In case of Indonesia, where mobile operator competition is so tight (8-full mobility operators), we think the best pricing strategy for mobile operator to offer femtocell is flat fee strategy to any call and data access making through their office’s femtocell. The FAP can be subsidized by the operator and consider the cost into the tariff.

6.4.4 Business model

This section highlight the rationale of how a mobile operator creates, delivers, and captures value through femtocell (framework is taken from Business Model Generation, Alexander Osterwalder & Yves Pigneur, Self Published, Canada 2010).

The value of propositions of femtocell by mobile operators are giving better indoor quality of services, lower tariff (VoIP) and as an office community service. The values also covered are described in sections 6.2.1 and 6.2.2 above.
In this model the segment that targeted by mobile operator is corporate customers segment. Mobile operator usually assigns an account manager to do the marketing and sales activities such as: customer relationship, promotion, and deliver the femtocell services to corporate customers (see Figure 69).

![Figure 69. Femtocell business model](image)

To guarantee that corporate customers can use and receive the value propositions stated above, mobile operators need to do some key activities and set up key resources with partners or, by utilizing their own resources to deliver, create the value propositions.

The key resources that must provide are:
- Engineering to do the installation in customer sites and operation center
- The Femtocell access point,
- Backhaul access and mobile infrastructure to support the service.

The key activities to create the value propositions are:
- CPE/FAP installation,
- Management of mobile and backhaul network
- Interconnection management.

Pure mobile operator cannot offer the value proposition of femtocell by himself: they need to do a partnership with femtocell vendor to ensure the availability of CPE and also the ISP/Fixed operator to provide the backhaul access.
7 CONCLUSION

This deliverable aims at setting the scene of the scenarios, problem to be solved and assumptions for the project. Section 2 reviewed the high level scenarios; Section 3 provided more in-depth analysis of these scenarios. In Section 5, the main parameters that will be considered to analyze these scenarios in FREEDOM are given. Just before, Section 4 summarizes the requirements inherited from the analysis of these high level and operational scenarios. At last, section 6 provides a first insight of business models that could be related to femtocell deployment.

From this first analysis of scenarios as well as business opportunities, it appeared that the enterprise scenario (usage of femtocells in a corporate environment) is the most likely to be deployed by the operator, before a massive deployment of femtocells in individual homes.

This problems related to corporate deployment should be first addressed by the FREEDOM project. Moreover, the project is positioned in the ITU IMT.ADV family of technology, based on OFDM/OFDMA access, namely the evolution of LTE (LTE.ADV) and the evolution of WiMAX under the standardization of 802.16m. It appeared also that in the LTE context, both FDD and TDD are envisaged for providing Indoor coverage. Typically, a scenario for the European operator would be that the outdoor coverage could be provided in FDD but for Indoor, these operators could leverage their TDD licences (often got as a bundle with the FDD auction) to provide indoor coverage. This definitely leads to various interference and mobility scenario that could be addressed by the other WPs of FREEDOM.
APPENDIX A: PATH-LOSS MODELS

8.1 FAP to indoor UE

Recommendation ITU-R P.1238-6 [ITU1238] gives radio prediction methods for terminals (UE) located in the same building. In particular, it proposes a site-independent path-loss model with parameters defined in different frequency bands in range [300MHz; 100GHz] and various indoor environment types (residential, office, commercial).

The mean path-loss (dB) is expressed as:

\[ PL = -20 + 20 \cdot \log_{10}(f) + N \cdot \log_{10}(d) + L_f(n) \]  

(A1)

where:

- \( N \): distance power loss coefficient;
- \( f \): frequency, in MHz;
- \( d \): path-length between terminals, in meters, \( d > 1 \) m;
- \( L_f \): floor penetration loss factor, in dB;
- \( n \): number of floors between terminals.

Parameters defined in frequency band 1.8-2.0GHz are given in table below:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Residential</th>
<th>Office</th>
<th>Commercial</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N ) (dB)</td>
<td>28</td>
<td>30</td>
<td>22</td>
</tr>
<tr>
<td>( L_f ) (dB)</td>
<td>4 ( n )</td>
<td>15 + 4 ( n - 1 )</td>
<td>6 + 3 ( n - 1 )</td>
</tr>
<tr>
<td>Shadow fading std. dev. (dB)</td>
<td>8</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 36. Parameters of ITU-R P.1238-6 path-loss model in the 1.8-2.0GHz frequency band.

The floor loss is not linear. It takes into account the impact of external paths between floors, resulting from diffraction on window frames, or reflection on neighbor buildings. These external paths may become dominant for largest floor separations.

The ITU recommendation gives some additional guidelines:

- LOS paths have a distance power loss coefficient \( N \) of around 20;
- Paths along corridors may have a distance power loss coefficient \( N < 20 \);
- For long unobstructed paths, the first Fresnel zone breakpoint makes the distance power loss coefficient changed from about 20 to about 40.

This model could be considered suited to FREEDOM indoor predictions (all environments of interest are specifically addressed), however the formulation does not permit simple compatibility with indoor-to-outdoor and outdoor-to-indoor path-loss models (see hereafter).

Besides, the COST231 Multi-wall model [COST231] estimates the indoor path-loss from the number of walls (light internal walls or heavy walls) crossed by the direct-path, with losses depending on the...
material and width of the partitions. As in the ITU model, the floor loss is a non-linear function of the number of penetrated floors.

\[
PL = -27.6 + 20 \cdot \log_{10}(f) + 20 \cdot \log_{10}(d) + L_c + \sum_{i=1}^{W} L_{Wi} \cdot n_{Wi} + 18.3 \cdot n_f \left( (n_f+2)(n_f-1) - 0.5 \right)
\]

where

- \( L_c \): constant loss close to 0dB;
- \( W \): number of different wall types;
- \( n_{Wi} \): number of wall of type \( i \) crossed by the direct-path;
- \( L_{Wi} \): penetration loss for a wall of type \( i \), in dB;
- \( n_f \): number of floors between terminals.

Recommended values at frequency 1800MHz are:

- \( L_{Wi} = 3.4\, \text{dB} \) for light walls;
- \( L_{Wi} = 6.9\, \text{dB} \) for heavy walls.

The formulation given by COST Multi-wall may be used as a site-specific indoor model, based on a precise description of partition locations and partition losses. It may be used as well as a site-independent model, replacing the sum of partition losses by a linear loss that depends on an average distance between partitions and an average partition loss.

COST231 multi-wall is modified as follows to predict the path-loss in the FREEDOM corporate layout (section 5.2):

\[
PL_{HN} = -27.6 + 20 \cdot \log_{10}(f) + 20 \cdot \log_{10}(d) + 0.7 \cdot d_{HN} + L_{Wi} \cdot q_{Wi} + 18.3 \cdot n_f \left( (n_f+2)(n_f-1) - 0.5 \right)
\]

where

- \( L_{Wi} \): is the average loss through office separation walls;
- \( q_{Wi} \): is the number of office separation walls crossed by the direct-path; \( q_{Wi} = 0 \) when FAP and UE are located in the same office;
- Losses inside the office are modeled by linear loss 0.7dB/m.

COST231 multi-wall is modified as follows to predict the path-loss in the FREEDOM residential layout (section 5.2):

\[
PL_{HN} = -27.6 + 20 \cdot \log_{10}(f) + 20 \cdot \log_{10}(d) + 0.7 \cdot d_{HN} + 18.3 \cdot n_f
\]

where losses inside the house are modeled by linear loss 0.7dB/m.

COST 231 announces that the shadowing component follows a lognormal distribution with standard deviation \( \sigma = 2.7-5.4\, \text{dB} \). A 4dB shadowing is assumed for FREEDOM simulations.

The 3GPP model [R4-071617] proposes a formulation similar to COST Multi-wall, using random variables to simulate the total number of internal walls and apartment separation walls between both terminals. This model gives realistic path loss distributions without considering a precise building layout. It is described for specific building structures (3-floor building with 10m×10m apartments, or 12m×12m houses) that are close or even similar to the FREEDOM building layouts.

The 3GPP model may be of interest for link-level simulations based on random path-loss predictions, but is not convenient for coverage predictions, or for predictions including space correlated shadowing.
The 3GPP model adapted to the FREEDOM corporate layout (section 5.2) is as follows:

$$PL_{IN} = -\frac{2L_{IN}}{1.6} + 20 \cdot \log_{10}(f) + 2U \cdot \log_{10}(a) + L_{IN} \cdot q_{IN} + L_{IW} \cdot q_{IW} + 18.3 \cdot n_F \left(\frac{n_F + 2}{n_F - 1} - 0.46\right)$$

(A5)

where

- $L_{IN}$ is the average loss through internal office walls;
- $q_{IN}$ is the random number of office internal walls crossed by the direct-path;
- $q_{IW}$ is the random number of office separation walls crossed by the direct-path;
- $q_{IW}$ and $q_{IW}$ are simulated following the process described in [R4-071617].

The 3GPP model adapted to the FREEDOM residential layout (section 5.2) is as follows:

$$PL_{IN} = -27.6 + 20 \cdot \log_{10}(f) + 20 \cdot \log_{10}(a) + L_{IN} \cdot q_{IN} + 18.3 \cdot n_F$$

(A6)

where

- $L_{IN}$ is the average loss through internal house walls;
- $q_{IN}$ is the random number of house internal walls crossed by the direct-path;
- $q_{IN}$ is simulated following the process described in [R4-071617].

Remark that all these indoor models may be not realistic at large distances, i.e. $d \geq 2000m$. At these distances, the path-loss may increase more rapidly because of obstruction of the Fresnel zone by the roof, the ceiling or furniture; in addition, indoor-outdoor-indoor paths may generate significant contributions, making the path-loss highly dependent on the environment geometry.

However no reference model for indoor large distances was found in literature.

8.2 Macro BS to street-level UE

The Okumura-Hata model [HATA80] and its COST231 extension [COST231] are widely used empirical models for prediction of path-loss with macro BS located above surrounding environment, and distances greater than 1km. The median path loss depends on the frequency, distance, terminal heights and environment. The Okumura-Hata model proposes formulations for open, suburban and urban environments in the frequency range [150MHz; 1GHz]. The COST231 Hata extension proposes formulations for urban environments in the frequency range [1.5GHz; 2GHz], as follows:

$$PL = -13.7 + 33.9 \cdot \log_{10}(f) - 13.82 \cdot \log_{10}(h_B) + \left(0.4 \cdot 6.55 \cdot \log_{10}(h_B) \right) \cdot \log_{10}(d) - a(h_B) + G$$

(A7)

where:

- $a(h_B) = \left(1.1 \cdot \log_{10}(f) - 0.7\right) \cdot h_B - \left(1.56 \cdot \log_{10}(f) - 0.8\right)$
- $G = 0$dB in medium-sized cities and suburban areas;
- $G = 3$dB in metropolitan areas;
- $f$: frequency, 1500MHz $\leq f \leq 2000$MHz;
- $d$: path-length, $d > 1000m$;
- $h_B$: height of the base-station above the average ground level, $30m \leq h_B \leq 200m$;
- $h_M$: height of the mobile-station above ground, $1m \leq h_M \leq 10m$. 

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COST231 Hata may be used in some simulations, however the ITU-R P 1411 model presented hereafter is preferred, as its validity range better matches the FREEDOM application domain (in terms of frequencies and distances).

The **ITU-R P.1411-5 recommendation** [ITU1411] proposes a NLOS macrocell path-loss model for distances less than 5km in frequency range [800MHz;5GHz] for urban The calculation is based on the well-known COST 231 Walfish-Ikegami model:

\[
PL = -27.6 + 20 \cdot \log_{10}(f) + 20 \cdot \log_{10}(d) + L_{RTS} + L_{MSD}
\]  

(A9)

where:
- \( f \): frequency, 800MHz \( \leq f \leq 5000\)MHz;
- \( d \): path-length, \(20\text{m} \leq d \leq 5000\text{m}\);
- \( L_{RTS} \): diffraction loss from rooftop to street, in dB;
- \( L_{MSD} \): reduction due to multiple screen diffraction past rows of buildings.

Following assumptions are made:
- Calculation of \( L_{RTS} \) depends on the orientation of the street where the mobile-station is located. Here this orientation is considered as unknown, then the street orientation correction factor gets an average value.
- The path-length is assumed long enough such that \( L_{MSD} \) is always calculated for grazing incidence.
- \( L_{MSD} \) is calculated from the formulation at \( f > 2000\text{MHz} \) in order to avoid discontinuities between 2000MHz and 2600MHz.

Finally,

\[
PL = -18.4 + 22 \cdot \log_{10}(f) + 38 \cdot \log_{10}(d) - 16 \cdot \log_{10}(1 + h_{BS} - h_{o}) + 20 \cdot \log_{10}(h_{o} - h_{UB}) - 10 \cdot \log_{10}(w) - 9 \cdot \log_{10}(b)
\]  

(A10)

where
- \( h_{o} \): average height of the buildings, in meters;
- \( h_{BS} \): height of the base-station above the ground, \( h_{o} < h_{BS} \leq 50\text{m}\);
- \( h_{UB} \): height of the mobile-station above the ground, \(1\text{m} \leq h_{MS} \leq 3\text{m}\);
- \( w \): average width of streets, in meters;
- \( b \): average building separation, in meters.

Parameters chosen for the FREEDOM urban and suburban models are:
- \( h_{BS} = 32\text{m}\);
- \( h_{UB} = 1.5\text{m}\);
- \( h_{o} = \begin{cases} \text{urban:15m} & ; \\ \text{suburban:12m} \end{cases} \);
- \( w = 20\text{m}\);
- \( b = 50\text{m}\).

These parameters make the ITU model close to COST231 Hata for distances greater than 1000m and base-station height 32m.

Consequently, the urban model is given by:

\[
P_{L\text{MACRO}} = \begin{cases} [2.0\text{GHz}] 25.9 & ; \\ [2.6\text{GHz}] 28.4 \end{cases} + 38 \cdot \log_{10}(d)
\]  

(A11)

And the suburban model is given by:
The ITU-R P.1411-5 recommendation proposes as well a NLOS macrocell path-loss model that is specific to the suburban environment, but the prediction is more complex. The formulation of the Walfish-Ikegami approach is preferred.

Remark about the 3GPP macro model. The 3GPP macro model that is expressed as

\[
PL_{\text{MACRO}} = \begin{bmatrix} 2.0GHz \end{bmatrix} 22.5 + \begin{bmatrix} 2.6GHz \end{bmatrix} 25.1 + 38 + 10 \log_{10}(d) \tag{A12}
\]

assumes that the base-station antenna is located 15m above the average building height, and sets the frequency at 2000MHz. This model is used in several 3GPP and FemtoForum studies.

The ITU-R P.1546 recommendation [ITU1546] gives path-loss predictions for macrocell base-stations and distances greater than 1km. The validity frequency range is [30MHz; 3GHz]. Predictions are adapted to over-sea, land, suburban, urban and mixed environments. The dependence of path-loss versus distance is given in curves (or numerical tables). Additional corrections are calculated for mobile-station height less than 10m above ground and short urban and suburban paths. This model may be suitable for long-range predictions.

8.3 FAP to outdoor street-level UE

When UE is in the close vicinity of the FAP building, the path-loss model for FAP to outdoor street-level UE is simply an extension of the single-floor indoor model:

\[
P_{\text{L_{IN-OUT-LOS}}} = P_{\text{L_{IN}}} + P_{\text{L_{OUT}}} + L_{EX} \tag{A13}
\]

where:

- \(d_{\text{IN}}\): indoor path-length, in meters, measured in the horizontal plane from the indoor terminal to the penetration point; the penetration point is assumed to be at the intersection between the building external wall and the direct-path;
- \(d_{\text{OUT}}\): outdoor path-length, in meters, measured in 3D;
- \(P_{\text{L_{IN}}}\): indoor loss calculated by the single-floor indoor model;
- \(L_{EX}\): average loss through the external wall, in dB; this loss is highly dependent on the building material, incidence angle and aperture distribution (windows, doors); we assume \(L_{EX} = 10 \log_{10}(d)\) in FREEDOM simulations.

An alternative model, more realistic, is based on a reciprocal of the COST 231 building penetration model, elaborated after measurements in the 900-1800MHz frequency range and distances up to 500m. The path-loss is estimated by the dominant contribution calculated along four paths perpendicular to the building exterior walls, as illustrated in Figure 70. Or, as suggested by COST 231, it may be obtained from the sum of the four contributions.
Figure 70: Outdoor-to-indoor (P1 to P2) or Indoor-to-outdoor paths (P2 to P1).

When the penetration point on the external wall is in line-of-sight (LOS) from the outdoor terminal, the path-loss is calculated as follows:

\[
PL_{\text{IN-out-LOS}} = -27.6 + 20 \cdot \log(f) + 20 \cdot \log(d_{\text{IN}} + d_{\text{OUT}}) + W_E + W_G \cdot \left(1 - \sin(\theta)\right)^2 + \frac{L_{\text{IN}}(d_{\text{IN}})}{L_E(d_{\text{IN}})}
\]

(A14)

where:

- \( f \): frequency in MHz;
- \( d_{\text{IN}} \): 2D indoor path-length, in meters, measured in the horizontal plane (i.e. in the floor of the indoor terminal);
- \( d_{\text{OUT}} \): outdoor path-length, in meters, measured in 3D;
- \( D \): 2D outdoor distance, in meters, measured in the direction perpendicular to the external wall;
- \( \theta \): incidence angle on the external wall, \( \sin(\theta) = \frac{D}{d_{\text{OUT}}} \); see Figure 71;
- \( W_E \): penetration loss for normal incidence (i.e. \( \theta = 90^\circ \)), in dB;
- \( W_G \): additional loss for grazing incidence (i.e. \( \theta = 0^\circ \)), in dB;
- \( L_{\text{IN}}(d_{\text{IN}}) \): indoor loss calculated from the 2D indoor path-length.
Figure 71: Distances along indoor-outdoor paths.

FREEDOM uses this COST 231 building penetration model to calculate the path-loss between FAP and outdoor street-level UE, with following parameters:

- $W_E = 7$ dB as recommended for concrete walls with normal window size;
- $W_{GE} = 20$ dB.

The indoor loss $L_{IN}(d_{IN})$ is not the one given by the COST 231 building penetration model, but the one given by the single-floor indoor path-loss model defined in section 8.1.

The outdoor path-loss model considers propagation below rooftops, which strongly depends on the environment geometry, then providing very different levels at a given distance. The microcell path-loss can be estimated by dual-slope models (using two different distance loss exponents) that represent the rapid increase of the path loss beyond a given breakpoint. In particular, the ITU-R P.1411-5 recommendation gives a solution for frequency range [300MHz; 3GHz], distances up to 3000m, and with transition between the LOS region (before corner) and NLOS region (after corner):

$$PL_{MICRO} = -50.5 + 45 \cdot \log(f) + 40 \cdot \log(d) + L_{URBAN}$$  \hspace{1cm} (A17)

where $L_{URBAN}$ depends on the urban category: 0dB for suburban, 6.8dB for urban and 2.3dB for dense urban/high-rise.

In FREEDOM scenarios, $PL_{MICRO}$ is given by:
- Urban scenario: \[ PL_{\text{MICRO}} = \begin{cases} [2.0\text{GHz}] 44.8 + 40 \cdot \log(d) & \text{if } 0.001 \leq p < 1 \\ [2.0\text{GHz}] 50.0 + 40 \cdot \log(d) & \text{otherwise} \end{cases} \] \hspace{1cm} (A18)

- Suburban scenario: \[ PL_{\text{MICRO}} = \begin{cases} [2.0\text{GHz}] 38.0 + 40 \cdot \log(d) & \text{if } 0.001 \leq p < 0.45 \\ [2.0\text{GHz}] 43.2 + 40 \cdot \log(d) & \text{otherwise} \end{cases} \] \hspace{1cm} (A19)

The ITU-R 1411-5 recommendation suggests as well a method to determine LOS/NLOS probabilities when no building layout is available. The maximal LOS distance with probability \( 0.001 \leq p < 1 \) is given by:

\[ d_{45}(p) = 212 \cdot \log(p)^2 - 64 \cdot \log(p) \quad \text{if } p \leq 0.45 \\
\]

\[ d_{\text{LOS}}(p) = 79.2 - 70 \cdot p \quad \text{otherwise} \] \hspace{1cm} (A20)

These probabilities were obtained from two cities in the United Kingdom.

Remark that empirical models cannot generally reproduce the large variety of propagation situations encountered in real microcell configurations. Only site-specific models (like ray-tracing) can provide realistic predictions.

### 8.4 FAP to indoor UE in another building block

The indoor-outdoor-indoor model for propagation between two different buildings is elaborated as an extension of the indoor-outdoor model presented here above.

As a first approach, valid only when external walls of both buildings are in line-of-sight (LOS), the path-length may be calculated as follows:

\[ PL_{\text{IN-OUT-OUT}} = -27.5 + 20 \cdot \log(f) + 20 \cdot \log((d_{\text{IN}})_1 + d_{\text{OUT}} + (d_{\text{IN}})_2) + (L_{\text{IN}})_1 + (L_{\text{IN}})_2 + 2d_{\text{EX}} \]

where:

- \((d_{\text{IN}})_1\) and \((d_{\text{IN}})_2\): indoor path-length in respectively the FAP and UE buildings, in meters, measured in the horizontal plane from the indoor terminal to the penetration point; the penetration points are assumed to be at the intersection between the building external walls and the direct-path;
- \(d_{\text{OUT}}\): outdoor path-length, in meters, measured in 3D;
- \((L_{\text{IN}})_1\) and \((L_{\text{IN}})_2\): indoor losses in respectively the FAP and UE buildings, calculated by the single-floor indoor model.
Figure 72: Distances along indoor-outdoor-indoor paths.

An alternative, constructed by the COST231 building penetration model, determines the dominant indoor-outdoor-indoor path considering indoor paths perpendicular to the external walls. The path-loss is calculated by the geometry illustrated in Figure 72:

\[
PL_{IN-OUT-IND-LOS} = -27.6 + 20 \cdot \log(f) + 20 \cdot \log\left(\frac{d_{IN1} + d_{OUT} + d_{IN2}}{\lambda}\right)
+ \left(\frac{W_{R} + W_{IR} \cdot (1 - \sin(\theta))}{\lambda} + L_{IN1}\right)
+ \left(\frac{W_{E} + W_{IE} \cdot (1 - \sin(\theta))}{\lambda} + L_{IN2}\right) \tag{A21}
\]

\[
PL_{IN-OUT-IND-NLOS} = PL_{MICRO}(d = (d_{IN1} + d_{OUT} + d_{IN2})
+ \left(\frac{W_{E} + W_{IE} \cdot (1 - \sin(\theta))}{\lambda} + L_{IN1}\right)
+ \left(\frac{W_{E} + W_{IE} \cdot (1 - \sin(\theta))}{\lambda} + L_{IN2}\right) \tag{A22}
\]

where \((...)_1\) and \((...)_2\) are respectively predicted in the FAP and UE buildings.

### 8.5 Macro BS to Indoor UE

In a first simple approach, the macro outdoor-to-indoor path-loss is obtained from the macro path-loss plus an average penetration loss \(P_{O2I}\). However this penetration loss is highly dependent on the building material, path geometry (path incidence on the external wall), surroundings (building density and building heights) and indoor penetration distance (light indoor: in a room with windows, deep indoor: in a room without window). Literature and radio planning guidelines give different penetration losses, but generally in the range from 10dB, typically for a light indoor terminal in a sparse urban or suburban environment, to 20dB, typically for a deep indoor terminal in a dense urban environment or inside a Hausmanian building.
When using a macro path-loss model for street-level UE, and predicting the indoor path-loss inside different floors, the path-loss must be reduced by a floor gain that represents the path-loss decrease versus UE height.

The **COST231 NLOS building penetration model** proposes a floor gain of 1.5-2dB for typical floor separations, i.e. less than 4m.

Finally, \[
PL_{\text{MACRO-IN}} = PL_{\text{MACRO}} - GL + nF + L_{OL}
\]  
(A21)

where
- \(PL_{\text{MACRO}}\): outdoor path-loss at street level, in dB;
- \(L_{OL}\): average penetration loss, in the range 10-20dB;
- \(GL = 2\text{dB/floor}\): floor gain, applicable only for floor height lower than the average building height;
- \(nF\): index of the UE floor, assuming 3m floor separation and \(nF = 0\) at the ground-floor.

Remark that the floor gain is valid only at lower floors. For UE located in the upper floors of high buildings, the path-length variation versus floor depends on the surrounding buildings and the whole path-geometry. For simplicity, we assume that the floor gain is limited to \(GL \times n_{\text{MEAN}}\), where \(n_{\text{MEAN}}\) is the average number of building floors in the environment.

An alternative to this simple approach is possible when UE is located within a building layout. This approach proposed by the **COST231 NLOS building penetration model** takes into account the indoor penetration distance \(d_{\text{IN}}\) from the closest penetration point (one of the four penetration points shown in Figure 70).

\[
L_{OL} = W_E + W_G + L_{\text{IN}}
\]  
(A22)

where
- \(W_E\): penetration loss for normal incidence (i.e. \(\theta = 90^\circ\)), in dB;
- \(W_G\): average additional loss, in dB;

The model is used with following parameters:
- \(W_E = 7\text{dB}\) as recommended for concrete walls with normal window size;
- \(W_G = 6\text{dB}\) as recommended at frequency 1800MHz.
- The indoor loss \(L_{\text{IN}}\) is not the one given by the COST 231 building penetration model, but the one given by the indoor path-loss model defined in section 8.1.

### 8.6 Site-specific models

**FAP to indoor UE:**

Building layout permits deterministic prediction of the path-loss, taking into account losses through floors, internal walls and doors located between both terminals. **COST231 multi-wall model** [COST231] is widely used in indoor radio predictions, where losses may be defined according to the material and width of the wall. It includes a floor loss that is a non-linear function of the number of penetrated floors.

More sophisticated techniques like **2D/3D ray-tracing** provide precise prediction of the radio wave propagation, but also multi-paths, by including impact of reflections and diffractions and EM properties of materials. Multi-paths may be used, in particular, to simulate the small-scale fading and fading within the signal frequency bandwidth.
Macro BS to UE:
The terrain is represented by a geographical map data (terrain altitude, clutter type, clutter height, building contours), enabling simulation of part of the shadow, based on the analysis of the path geometry and modelling of physical mechanisms.

The methods being commonly found in radio planning tools to predict path-loss for macro BS located above surrounding environment rely on the multiple knife-edge diffraction techniques (main obstacles encountered along the direct path are represented by knife-edges generating a diffraction loss), as Deygout or Epstein-Peterson techniques [SAU99], originally elaborated for rural, but successfully used in urban areas as well.

The ITU-R P.1546 [ITU1546] and ITU-R P.1411 [ITU1411] recommendations propose as well methods to get site-specific predictions, based e.g. on the effective base station height, terrain clearance angle, knife-edge diffraction, etc.

More sophisticated techniques, relying on an approximate of Maxwell’s equation solution, like 2D/3D ray-tracing [SAU99], give even further precision in dense urban areas and can be employed to deal with BS located low. They predict as well multi-path channel properties. Fast ray-tracing techniques are commonly used in radio planning tools.

FAP to outdoor street-level UE:
Building layout permits to predict the penetration loss in a deterministic way, inspecting if the path crosses the external wall, a window or a door.

Coupling this building layout with 2D/3D ray-tracing techniques provide very realistic predictions, for close and even distant outdoor terminals. In the latter case, the path loss prediction takes advantage of the surrounding terrain representation to include impact of outdoor interactions (obstruction, reflection, diffraction).

Macro BS to indoor UE:
In first approximation, the building may be represented by its external contours. The geometry of the outdoor and indoor paths are computed by a site-specific model. The penetration loss depending on the external wall nature plus an in-building loss depending on the indoor path length (accounting for internal walls and furniture impact in a statistical way) are summed to the outdoor path-length.

The building can be represented with more details to get very realistic predictions, including internal partitions, external walls, windows, etc. Then the penetration loss is calculated in a deterministic way, verifying if the path crosses the external wall, a window or a door. The in-building loss depends on the obstacles found between the indoor terminal and the penetration point.
9 APPENDIX C: INTERFERENCE POWER MODELS

In [HAEN08] a unified framework is introduced that permits the geometric characterization of fading by incorporating the fading process into the point process model. Assuming nodes are distributed in a stationary Poisson point process (PPP) in $\mathbb{R}^d$ with intensity $\lambda$ the properties of the point processes that describe the path loss with fading are analyzed. Let the set $\{y_i\}, i \in \mathbb{N}$, consist of the points of a stationary Poisson point process in $\mathbb{R}^d$ of intensity 1, ordered according to their Euclidean distance $\|y_i - o\|$ from the origin $o$. Define a new one dimensional (generally inhomogeneous) PPP $\{r_i = \|y_i - o\|\}$ such that $0 < r_1 < r_2 < ...$ almost surely. Let $\alpha > 0$ be the path loss exponent of the network and $\Phi = \{x_i - r_i^\alpha\}$ be the path loss process. Let $\{f_1, f_2, f_3, ...\}$ be an i.i.d. stochastic process with $f$ drawn from a distribution $F \triangleq F_t$ with unit mean. Finally, let $\Xi = \{\xi_i = x_i / f_i\}$ be the path loss process with fading. To obtain closed form expressions, still using a relevant channel model, it is used the Nakagami-m power fading model, whose distribution and density are as follows:

$$F(x) = 1 - \frac{\Gamma_w(m,mx)}{\Gamma(m)} \quad (B1)$$

$$f(x) = m^x x^{m-1} \exp(-mx) / \Gamma(m) \quad (B2)$$

where $\Gamma_w$ denotes the upper incomplete gamma function. The Nakagami-m model is useful as it incorporates the Rayleigh fading case as well as the deterministic case (for $m$ going to infinity). This distribution is a single parameter version of the gamma distribution where both parameters are the same and such that the mean is always 1. Often, it is considered the standard network that has the following parameters: $\delta = d / \alpha = 1$ and $\delta = d / \alpha = 1$ (path loss exponent equal to the number of dimensions) and Rayleigh fading, i.e., $F(x) = (1 - \exp(-x))u(x)$. Let $\Lambda$ be the mean measure associated with $\Phi$, i.e., $\Lambda(B) = E[\Phi(B)]$ for Borel $B$ and $\lambda(x) = d\Lambda(x) / dx$ be the density of $\Phi$, the following properties are true:

- $\Lambda(x) = c_d x^\delta \Lambda(x) = c_d x^\delta$ and $\lambda(x) = c_d x^\delta \lambda(x) = c_d x^\delta$; for $\delta = 1$, $\Phi$ has a constant intensity;
- $r_i r_i^{-\delta}$ is governed by the generalized gamma probability density function:

$$f_{\cdot_i} = \exp(-r_i) \frac{d(c_d r_i^{\delta})}{r \Gamma_i} \quad (B3)$$

And $x_i$ is distributed according to the cumulative distribution function

$$F_{x_i}(x) = 1 - \frac{\Gamma_w(i,c_d x^\delta)}{\Gamma(i)}$$

The expected path loss without fading is:

$$E[x_i] = c_d^{-\delta} \frac{\Gamma(i + 1/\delta)}{\Gamma(i)}$$

The distribution function of $\xi_i, \xi_i$ is defined as:
\[ F_{\xi} = 1 - \int_0^{\infty} F\left( \frac{r}{x} \right) \left( e^{c_d \delta r^{\delta-1}} \exp(-c_d r^\delta) \right) \frac{dr}{\Gamma(i)} \]

For \( \delta = 1 \) and Nakagami-\( m \) fading, the PDF of \( \zeta \) is:

\[ f_{\zeta_i}(x) = \frac{m^{m+1}}{(m+c_d x)^{m+1}} \frac{m+i-1}{m} c_d x^{i-1} \]

In particular,

\[ F_{\zeta_i}(x) = 1 - \left( \frac{m}{c_d x + m} \right)^m \]

and

\[ E[\zeta_i] = \frac{m}{c_d (m-1)} \quad \text{for } m=1 \]

\[ Var[\zeta_i] = \frac{m^2 i (m+i-1)}{c_d^2 (m-1)^2 (m-2)} \quad \text{for } m>2 \]

For the standard networks:

\[ F_{\zeta_i}(x) = \left( \frac{c_d x}{c_d x + 1} \right)^i \]

Wireless network performance is mostly interference-limited, and a large number of users contribute to the interference in vastly varying magnitudes. The received signal power is random due to the random spatial distribution of the users, shadowing and fading. As shown in [HAEN09], the SINR for a receiver placed at the origin \( o \) can be written as:

\[ \text{SINR} = \frac{S}{W + I} \quad \text{where } I = \sum_{i \in T} P h_i \left( \| y_i - o \| \right) \]

where \( S, W, \) and \( I \) are the desired signal, noise, and interference powers, respectively. The summation for \( I \) is taken over the set of all interfering transmitters \( T \), \( P_i \) is the transmit power, \( h_i \) is a random variable that characterizes the cumulative effect of shadowing and fading, and \( l \) is the path loss function, assumed to depend only on the distance \( \| y_i - o \| \) from the origin of the interferer situated at position \( y_i \) in space. Often \( l \) is modelled as a power law, or in environments where absorption is dominant, as an exponential law. In a large system, the unknowns are \( T, h_i, h_1, \) and \( x_i \), and perhaps \( P_i \), but it is the locations of the interfering nodes that most influence the SINR levels, and hence, the performance of the network.

The interference is a function of the underlying node distribution (and mobility pattern for mobile networks) and the channel access scheme. Denoting with \( I(\|x\|) \) the path loss function arising in a link of distance \( x \), and assuming the same transmit power for all nodes, the aggregate interference received in a point \( x \) from transmitters located in points \( \{Y_i\} \) modelled as a PPP can be defined as follows:
Where \( \Phi_i \) is typically a subset of a larger point process \( \Phi \) since it constitutes the nodes selected by the MAC scheme to transmit concurrently. This formula shows that the aggregated interference can be modelled as a shot noise, with impulse response \( g(x) \) equal to \( I(\|x\|) \). For example, if nodes in a homogeneous PPP of intensity 1 transmit independently and randomly with probability \( p \) (slotted ALOHA), \( \Phi_i \) is a PPP with intensity \( p \). To analyze the distributional properties of \( I(x) \), the analogy to shot noise processes can be used to derive the Laplace transform of the interference as shown in [HAEN08].

**Interference Model 2**

In [SALB08], it is proposed an analytical framework for the statistical characterization of the amount of interference provided by nodes located on a given region of limited area in a propagation environment characterized by a deterministic path-loss and shadowing. The analysis is focused on three simplified scenarios: i) nodes belonging to circular area whose distance from the receiver is arbitrary; ii) nodes located in a circular annulus around the receiver; iii) nodes located in a circular area around the receiver. Scenario a) can be used to characterize the interference originated by a hot spot. Scenario b) finds application in the analysis of networks that are completely surrounded by interferers. Finally, scenario c) can be used to characterize the amount of the self-interference that is the interference coming from nodes belonging to the same network. The scenario is characterized by a Poisson spatial distribution of nodes with density \( \rho \). The probability of having one node in the infinitesimal area \( \delta A \) is therefore \( \rho \delta A \). It is assumed that all the nodes in the interfering areas use the same value of transmitted power \( P_T \). Let's consider two nodes, the receiver \( N_0 \) and the source of interference \( N_1 \) which is located in one of the areas of interest. The power loss between the two nodes and the channel gain are respectively, \( L = kD^\beta \) and \( G = 1/LG = 1/L \), where \( k \) is a propagation coefficient, \( D \) is the distance from the transmitter to the receiver, \( \beta \) is the attenuation coefficient which commonly ranges from 2 to 5, and finally, \( S \) is the long term (shadowing) fading component. In logarithmic scale

\[
\hat{L} = 10\log_{10} k + \beta 10\log_{10} D + 10\log_{10} S + k_\beta \ln D + \hat{S} \\
\hat{L} = 10\log_{10} k + \beta 10\log_{10} D + 10\log_{10} S = \hat{R} + k_\beta \ln D + \hat{S}.
\]

Owing to the log-normal distribution of \( S \), \( \hat{S} \) is a Normal random variable with zero mean and variance \( \sigma^2 \). This propagation model is only valid when the distance between the nodes is larger than some defined wavelength. A practical approach to overcome this limitation is to suppose the existence of a "dead-zone" around the reference point having a radius of 1 meter, which is supposed to be free of nodes. A more realistic approach is based on the use of a two-slope propagation model. Considering a generic scenario where \( A(d) \) is the area of the surface identified by the intersection between the interfering area and a circumference of radius \( d \) centered at the receiver. The probability that \( D \leq d \) is given by the general expression:

\[
F_{D}(d) = \Pr(D \leq d) = \frac{A(d)}{A} \tag{B8}
\]

where \( A \) is the interfering area. The joint PDF of \( D \) and \( \hat{S} \) can hence be written as

\[
f_{D,\hat{S}}(d, \hat{S}) = \frac{A'(d)}{A} \frac{e^{-\hat{S}^2/(2\sigma^2)}}{\sigma\sqrt{2\pi}} \tag{B9}
\]
where $A'(d) = dA(x) / dx$, $s \in (-\infty, +\infty)$, and $d$ ranges from the distance between the receiver and the closet point of the interfering area and the distance between the receiver and the farthest one. Making a change of variable, the joint distribution of $G$ and $\hat{Y}$ can be written as:

$$f_{G,\hat{Y}}(g, \hat{y}) = \frac{A'(\phi(g, \hat{y}))}{A} \frac{e^{-\hat{y}^2/(2\alpha^2)}}{\sigma \sqrt{2\pi} \alpha^{1/\alpha}} \frac{e^{\frac{\ln(10) S}{10\alpha}}}{g^{1+1/\alpha}}$$  \hspace{1cm} (B10)

Note that only the term $A'/A$ depends on the shape of the external area. The general expression can be specialized for the cases of interest previously described. In particular, in [SALB08] it is possible to find expressions in closed form of the PDF of the channel gain $G$, obtained for each geometry, by integrating $\hat{Y}$ over its range of definition. To characterize the amount of interference received by a node, it is assumed that all the nodes in the considered area are source of interference. This is a typical assumption in the presence of multiple access schemes such as spread spectrum techniques where all the nodes transmit in the same frequency band. In an OFDMA based system only a subset of users may interfere. Owing to the PPP model considered for the nodes’ positions, the number of terminals in the interfering area, denoted by $N$, is a Poisson random variable with mean value $\rho A$ (where $A$ is the area of the considered surface). It is also assumed that the interfering nodes transmit with a given probability $P_A$. Under this latter hypothesis, the number of transmitting nodes can still be modelled as the Poisson distribution with mean given by $\mu_t = \rho P_A A$. A closed form expression for the moments of the interference is given in [SALB99] and here it is shown the final expression for the first three moments:

$$\mu_t = P_T \mu_N \mu_G$$

$$\mu_t^{(2)} = P_T^2 \mu_N \left( \mu_G^{(2)} + \mu_N \mu_G^2 \right)$$

$$\mu_t^{(3)} = P_T^3 \mu_N \left( \mu_N^2 \mu_G^3 + 3 \mu_N \mu_G \mu_G^{(2)} + \mu_G^{(3)} \right)$$

The expressions of the moments are valid for any scenario and require only the knowledge of $\mu_N$ and of $\mu_G$. Expressions in closed form for the scenarios taken in consideration are given in [SALB08].

**Interference Model 3**

In [GHAS08] a statistical model of interference aggregation in spectrum-sensing cognitive radio (CR) networks is developed. It is taken into account the random variations in the number and location of CRs as well as propagation characteristic. Motivated by the interference temperature concept, it is assumed that the primary receiver (in this case the Macro BS or, when active, another close FAP), is capable of tolerating a maximum value of interference power. Interference levels higher than this threshold are considered harmful and should be avoided. In order to ensure that the interference constraint is satisfied, the CRs should be able to reliably detect any active transmission which they may harmfully interfere with. Let $P_b$ and $N$ denote the transmit power of the primary user and the power of the background additive white Gaussian noise, respectively. The received SNR at a CR FAP can be expressed as:

$$\gamma(r, x) = \frac{P_b x r^{-\alpha}}{N}$$  \hspace{1cm} (B11)
Where \( x \) is a unit mean random variable with PDF \( f_X(x) \) representing the frequency flat fading effects, \( r \) is the distance and \( \alpha \) is the path loss exponent. In general, the probability that a CR successfully detects the presence of an existing communication over a sub channel improves with increasing SNR of the receiving signal and as such, may be denoted by the following threshold-based detection model:

\[
P_d(\gamma) = \begin{cases} 
0 & \gamma \leq \gamma_0 \\
1 & \gamma > \gamma_0 
\end{cases}
\]

In words, the detection is successful if the received SNR is above a certain threshold \( \gamma_0 \). If the received SNR is below \( \gamma_0 \), then a white space will be declared and the CR FAP will start to interfere with another existing communication. Therefore, \( \gamma_0 \) may be viewed as a measure of the cognitive radio's detection sensitivity.

It is often more convenient to use the following equivalent representation:

\[
P_d(\gamma(r,x)) = \begin{cases} 
0 & r^{1/\alpha}x > R_s \\
1 & r^{1/\alpha}x \leq R_s 
\end{cases}
\]

where \( R_s = (CP_b / \gamma_0 N)^{1/\alpha} \). Then, \( R_s \) may be interpreted as the sensing range of the cognitive radios with non fading AWGN channels. It is assumed a homogeneous spatial Poisson point process \( \Pi' \) of intensity \( \lambda \). That is, the number of transmitters in any given region of area \( A \) is a Poisson random variable with parameter \( \lambda A \), and the number of transmitters in any two disjoint regions are independent random variables. In this context, the effect of fading can be interpreted as a mark associated with the underlying point of \( \Pi' \). Since each point of \( \Pi' \) is marked independently of the others, by marking theorem, the marked process \( \Pi \) is a Poisson Point Process with intensity \( \lambda f_X(x) \).

In such a scenario, the normalized aggregate interference at the primary receiver may be written as:

\[
I = \sum_{i \in \Pi} x_i r_i^{-\alpha}
\]

Where \( \Pi_i \) is the set of interfering cognitive radios. In particular, a CR within \( \Pi \) belongs to \( \Pi_i \) and hence contributes to the aggregated interference, only if it fails the detection procedure. As a consequence, \( \Pi_i \) may be considered as an inhomogeneous PPP obtained via location-dependent thinning of \( \Pi \) and how can be characterized by intensity:

\[
\lambda_i(r,x) = \lambda f_X(x) \left[1 - P_d(\gamma(r,x))\right]
\]

In \[GHAS08\] it has been used to derive exact and closed-form expressions for the cumulants of the aggregate interference under various fading distributions. Having the exact cumulants (and hence moments) of the aggregated Interference at our disposal, it is possible to employ various methods to approximate the distribution of the aggregate interference. By virtue of the central limit theorem (CLT), one may be tempted to approximate the distribution of \( I \) with a Gaussian PDF. However, inspection of the cumulants shows that the PDF of \( I \) is positively skewed and thus deviates from normality. This issue is more pronounced when CRs employ less sensitive detectors since there will be a higher chance of having strong interferers located close to the primary receiver which in turn results in a heavier right tail for the distribution of \( I \). A simple alternative method, commonly used for modelling positively skewed random variables, is the log-normal distribution. In \[GHAS08\] it is proposed to approximate \( I \) with a three-parameter shifted log-normal (SLN) random variable \( Z \) with the following PDF:

\[
f_Z(z) = \frac{1}{\sigma(z-c)\sqrt{2\pi}} e^{-(\log(z-c)-\mu)^2/2\sigma^2}, \quad z>c
\]

where \( c \) is the shift parameter. This enables us to match the skewness of \( Z \), in addition to its mean and
variance, to those of $I$. As shown in [GHAS08], applying the method of the moments, $\mu$, $\sigma^2$ and $c$ may be obtained in terms of the first three cumulants of $I$ and consequently,

$$P[I > z] \approx Q\left(\frac{\log(z - c) - \mu}{\sigma}\right)$$

(B14)