PROJECTE FINAL DE CARRERA

ACCESS MODES BASED ON COORDINATED MULTIPOINT FOR RELAY TRANSMISSIONS IN 4G SYSTEMS

Estudis: Enginyeria de Telecomunicació
Autor: Sandra Lagén Morancho
Director: Adrián Agustín de Dios
Ponent: Josep Vidal Manzano
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Resum del projecte

La naturalesa i la política de regulació fan de l'espectre radioelèctric un recurs escàs. En aquest sentit, els dissenyadors de sistemes afronten el repte de millorar l'eficiència espectral del sistema i proporcionar una cobertura homogènia per als sistemes cel·lulars. En les properes generacions de sistemes cel·lulars, com els basats en el Third Generation Partnership Projects Long-Term Evolution Advanced (3GPP LTE-A), s'utilitzaran terminals multi-antena, desplegaments de xarxa heterogenes i planificacions de xarxa amb reúss freqüencial complert. En primer lloc, l'ús de múltiples antenes en el transmissor i el receptor (coneguts com sistemes MIMO) té la gran avantatge que, sense augmentar la potència transmesa o el ample de banda, la capacitat de l'enllaç punt a punt s'escala de forma lineal amb el nombre mínim d'antenes transmissors i receptores. En segon lloc, el desplegament d'una xarxa heterogènia és una manera simple i efectiva en cost per aconseguir guanys a través de la mitigació de la interferència intra-cel·la (interferència entre terminals d'una mateixa cel·la) mitjançant el desplegament de punts d'accés addicionals, com repetidors (RSs) o femto-cel·les (FAPs), per servir àrees més petites. En tercer lloc, la reutilització completa de freqüències és una estratègia per simplificar el desplegament d'una xarxa, tot i que genera una considerable interferència inter-cel·la (interferència entre terminals de diferents cel·les) en els extrems de la cel·la; fet que convergeix en una necessitat les estratègies avançades de gestió de la interferència.

Una manera d'explotar o mitigar la interferència inter-cel·la sota reutilització freqüencial completà és a través de la coordinació entre estacions base (BSs) o diferents cel·les. Per això, les transmissions amb coordinació multipunt (CoMP), on vàries estacions base es coordinen per transmetre, són un dels conceptes més prometedors per als sistemes cel·lulars de pròximes generacions per tal de millorar la tassa de transmissió als extrems de la cel·la, més enllà del que és possible amb un sistema MIMO-OFDM en les primeres versions del LTE o el WiMAX. A més, si s'aplica processat i transmissió conjunta en CoMP (CoMP-JP), permet obtenir grans avantatges del guany de multiplexat combatent alhora la interferència inter-cel·la.

En aquest projecte s'estudia la combinació de CoMP i xarxes heterogènies en sistemes MIMO-OFDM, per tal de millorar la eficiència espectral cel·lular del sistema (és a dir, la tassa de transmissió agregada en una cel·la per unitat d'espectre) i garantir la homogeneïtats dels serveis.

En la primera part del projecte, diverses tècniques de coordinació basades en CoMP-JP són descrites i avaluades. Considerem una xarxa on múltiples estacions base cooperen per a les transmissions en l'enllaç descendent d'un sistema LTE-A, i un escenari amb una distribució de tràfic homogènia en la macrocel·la (és a dir, usuaris uniformment distribuïts). El rendiment del CoMP-JP es compara amb les xarxes cel·lular convencionals on la transmissió es fa sense coordinació d'estacions base. Es demostra que un esquema basat en CoMP-JP és capaç de reduir la interferència inter-cel·la, millorant significativament la capacitat en l'enllaç de baixa de les xarxes cel·lulars.

En la segona part del projecte, es considera un desplegament amb repetidors per tal de millorar el rendiment del sistema (també en termes de servei homogeni com d'eficiència espectral) sense la necessitat d'incrementar la densitat d'estacions base. Atès que el RS disposa d'una connexió sense fils fins a l'escà de base i que considerem repetidors half-dúplex (no poden transmetre i rebre alhora), la transmissió es divideix en dues fases en les que els missatges s'envien primer des de les BSs als RSs i després des dels RSs als usuaris mòbils (UEs). En l'enllaç BS-RS, diverses BSs cooperen per transmetre en l'enllaç descendent seguint una estratègia basada en CoMP. Amb l'optimització conjunta dels recursos assignats a l'accés BS-RS i l'accés RS-UE, és possible aprofitar els beneficis del CoMP i, juntament, combatre els efectes del pathloss i el shadowing gràcies al desplegament de repetidors. Es demostra que el problema és convex sota funcions objectiu convencionals de qualitat de servei (QoS). Dues solucions sub-òptimes i de baixa complexitat són proposades i avaluades. Finalment, la durada de les fases de recepció i
transmission in the relay transmissions are fixed, in such a way that the interference induced by other cells is stationary during the interval of transmission. In this case, a low-complexity algorithm is proposed. The performance of CoMP-JP utilized in the first link of a transmission with relays, compares with a transmission with relays without cooperation of the BSs. The results show the adequate application of CoMP in relay transmissions, which improves compared to the transmission with relays without coordination of BSs.

Having studied the performance of a homogeneous network (with only BSs) and a heterogeneous network with BSs and RSs in a homogeneous traffic scenario, it is observed that deploying relays makes sense in deployments where the distance between BSs is large. However, it does not happen in hotspots where most users are close or inside buildings (as in a corporate scenario).

With this motivation, in the third part of the project, a femto-relay analysis is developed to complement the deployment of FAPs and improve indoor coverage. Although a transmission with relays cannot compete with a transmission with FAPs, we can still benefit by deploying RSs to improve the system performance without increasing the density of BSs and improving service for those indoor users who do not have any FAP active. To achieve the benefits provided by the deployment of relays, advanced MIMO access schemes based on CoMP for the BS-RS link, which provide better spectral efficiency and coverage than conventional systems based on CoMP without relays. To minimize interference between the two networks, sub-frames are assumed orthogonal in mode of access TDD (duplexed per division in time) of LTE-A for transmissions through RSs and through FAPs. The number of sub-frames assigned to each network is optimized following two different criteria, depending on a design parameter that allows the network operator to balance resources between users served through RSs or through FAPs. The analysis results allow to draw important conclusions: the deployment of relays allows to improve the traffic of the worst users and the coverage in hotspot scenarios, and in addition they can complement deployments based on FAPs to improve the spectral efficiency of the system in deployments with low density of FAPs.
Resumen del proyecto

La naturaleza y la política de regulación hacen del espectro radioeléctrico un recurso escaso. En este sentido, los diseñadores de sistemas se enfrentan al reto de mejorar la eficiencia espectral del sistema y proporcionar una cobertura homogénea para los sistemas celulares. En los sistemas celulares próximas generaciones, como los basados en el Third Generation Partnership Projects Long-Term Evolution Advanced (3GPP LTE-A), se utilizarán terminales multi-antena, despliegues de red heterogéneos y planificaciones de red con reuso frecuencial completo. En primer lugar, el uso de múltiples antenas en el transmisor y el receptor (conocidos como sistemas MIMO) tiene la gran ventaja que, sin aumentar la potencia transmitida o el ancho de banda, la capacidad del enlace punto a punto se escala de forma lineal con el número mínimo de antenas en transmisión y en recepción. En segundo lugar, el despliegue de una red heterogénea es una manera simple y efectiva en coste para conseguir ganancias a través de la mitigación de la interferencia intra-celda (interferencia entre terminales de una misma celda) mediante el despliegue de puntos de acceso adicionales, como repetidores (RSs) o femto-celdas (FAPs), para servir áreas más pequeñas. En tercer lugar, la reutilización completa de frecuencias es una estrategia para simplificar el despliegue de una red, a pesar de que genera una importante interferencia inter-celda (interferencia entre terminales de diferentes celdas) en los extremos de la celda; hecho que convierte en una necesidad las estrategias avanzadas de gestión de la interferencia.

Una forma de explotar o mitigar la interferencia inter-celda bajo reutilización frecuencial completa es a través de la coordinación entre estaciones base (BSs) o diferentes celdas. Por esta razón, las transmisiones con coordinación multipunto (CoMP), donde varias estaciones base se coordinan para transmitir, son uno de los conceptos más prometedores de los sistemas celulares de próximas generaciones para mejorar la tasa de transmisión en los extremos de la celda, más allá de lo que es posible con un sistema MIMO-OFDM en las primeras versiones del LTE o el WiMAX. Además, si se aplica procesado y transmisión conjunta en CoMP (CoMP-JP) permite obtener grandes ventajas de la ganancia de multiplexado combatiendo a la vez la interferencia inter-celda.

En este proyecto se estudia la combinación de CoMP y redes heterogéneas en sistemas MIMO-OFDM, con el fin de mejorar de la eficiencia espectral celular del sistema (es decir, la tasa de transmisión agregada en una celda por unidad de espectro) y garantizar la homogeneidad de los servicios.


En la segunda parte del proyecto, se considera un despliegue de repetidores para mejorar el rendimiento del sistema (tanto en términos de servicio homogéneo cómo de eficiencia espectral) sin necesidad de incrementar la densidad de estaciones base. Dado que el RS dispone de una conexión inalámbrica hasta la estación base y que consideramos repetidores half-duplex (no pueden transmitir y recibir a la vez), la transmisión se divide en dos fases en las que los mensajes se envían primero desde las BSs a los RSs y después desde los RSs a los usuarios móviles (UEs). En el enlace BS-RS, varias BSs cooperan para transmitir en el enlace descendente siguiendo una estrategia basada en CoMP. Con la optimización conjunta de los recursos asignados al acceso BS-RS y el acceso RS-UE, es posible aprovechar los beneficios del CoMP-JP y, juntamente, combatir los efectos del pathloss y el shadowing gracias al despliegue de repetidores. Se demuestra que el problema es convexo bajo funciones objetivo
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Consideraciones de calidad de servicio (QoS). Dos soluciones sub-óptimas y de baja complejidad son propuestas y evaluadas. Finalmente, se propone fijar la duración de las fases de recepción y transmisión en los repetidores, de forma que la interferencia inducida por otras celdas sea estacionaria durante el intervalo de transmisión. En este caso, se desarrolla un algoritmo de baja complejidad. El rendimiento de CoMP-JP utilizado en el primer link de una transmisión con repetidores, se compara con una transmisión con repetidores sin cooperación de las BSs. Los resultados muestran la adecuada aplicación del CoMP en las transmisiones con repetidores, dado que se obtienen ganancias significativas respecto a la transmisión con repetidores y sin cooperación de BSs.

Una vez estudiado el rendimiento de una red homogénea (con sólo BSs) y una red heterogénea con BSs y RSs en un escenario con distribución de tráfico homogénea en la macrocelda, se observa que tiene sentido desplegar repetidores en escenarios donde la distancia entre BSs es elevada. Aunque esto no pasa en escenarios hotspot, donde la mayoría de los usuarios están cerca o dentro de los edificios (cómo en un escenario corporativo).

Con esta motivación, en la tercera parte del proyecto, se desarrolla un análisis femto-repetidores para evaluar las complementariedades entre ambas redes en escenarios hotspot. El despliegue de repetidores se propone para complementar el despliegue de FAPs y mejorar la cobertura en interiores. A pesar de que una transmisión con repetidores no puede competir con una transmisión con FAPs, todavía podemos obtener beneficios de desplegar RSs para mejorar el rendimiento del sistema sin incrementar la densidad de BSs y mejorar el servicio de aquellos usuarios de interior que no tienen ninguna FAP a la que asociarse. Para conseguir los beneficios dados por el despliegue de repetidores, esquemas de acceso MIMO avanzados basados en CoMP son definidos para el enlace BS-RS, el cual proporciona una mejor eficiencia espectral y cobertura que los sistemas convencionales basados en CoMP sin repetidores. Para minimizar la interferencia entre las dos redes, se asumen sub-tramas ortogonales en modo de acceso TDD (time division duplex) del LTE-A para las transmisiones a través de los RSs y a través de las FAPs. El número de sub-tramas asignadas en cada red se optimiza siguiendo dos criterios diferentes, los cuales dependen de un parámetro de diseño que da al operador de red un grado de flexibilidad para poder equilibrar los recursos hacia los usuarios servidos a través de los RSs o a través de las FAPs. Los resultados permiten extraer conclusiones importantes: el despliegue de repetidores permite mejorar la tasa de los peores usuarios y la cobertura en escenarios hotspot, y además puede complementar los despliegues basados en FAPs para mejorar la eficiencia espectral del sistema en despliegues con baja densidad de FAPs.
Abstract

Nature and regulation policy make radio spectrum scarce. In this regard, system designers are pushed towards the challenge of enhancing system spectral efficiency and providing homogeneous coverage for wireless systems. Next generation cellular systems, such as ones based on the Third Generation Partnership Projects Long-Term Evolution Advanced (3GPP LTE-A), will employ multi-antenna terminals, heterogeneous network deployments and full frequency reuse planning. Firstly, the use of multiple antennas at the transmitter and the receiver (MIMO systems) has the great advantage that, without increasing power or bandwidth, the capacity of a point-to-point link is scaled linearly with the minimum number of transmit and receive antennas. Secondly, a heterogeneous network is a simple and cost-effective way to achieve much of the gains of intra-cell interference mitigation (i.e. interference between terminals belonging to the same cell) by including additional access point, like relay stations (RSs) or femto access points (FAPs), to serve smaller areas (which if regular BS are used is an expensive option). Thirdly, the full frequency reuse is a strategy to simplify network deployment, even it creates significant inter-cell interference (i.e. interference between terminals of different cells) at the cell-edge; thus rendering advanced interference management strategies a necessity.

One way to exploit or mitigate the inter-cell interference under full frequency reuse is by the coordination between base stations (BSs) or different sites. For that reason, coordinated multipoint transmissions (CoMP) is one of the promising concepts for next generation cellular systems to improve cell edge user data rate and spectral efficiency, beyond what is possible with MIMO-OFDM in the first versions of LTE or WiMAX. Moreover, CoMP when joint processing and transmission is applied (CoMP-JP) allows obtaining full advantage of the multiplexing gains with jointly combating inter-cell interference.

In this project we study the combination of CoMP and heterogeneous networks for MIMO-OFDM systems, so as to improve the system cellular spectral efficiency (i.e., aggregated cell data rate per unit of spectrum) and the service homogeneity.

In the first part of the project, various coordination techniques based on CoMP-JP are described and evaluated. We consider a network where multiple BSs cooperate for the transmissions in the downlink of an LTE-A system, and a scenario with homogeneous traffic distribution is deployed (i.e. users uniformly distributed in the macrocell). The performance of CoMP-JP is compared to the conventional cellular networks without BSs coordination. It is shown that CoMP-JP is able to reduce inter-cell interference, improving significantly the capacity on the downlink cellular networks.

In the second part of the project, a deployment with RS is developed to improve the system performance (both in terms of cell edge and cellular spectral efficiency) without increasing the BS density. Since RSs are wirelessly connected to the BSs and half-duplex relay stations are considered (they cannot receive and transmit simultaneously), the transmission is divided into two phases in which messages are sent first from BSs to RSs and afterwards from RSs to mobile stations (UEs). In the BS-RS link, multiple BSs cooperate for the downlink following a CoMP strategy. With the joint optimization of the resources allocated to the wireless backhaul (BS-RS link) and to the RS-UE access, it is possible to exploit the benefits of CoMP along with combating the pathloss and shadowing effects thanks to the use of relay stations. The problem is shown to be convex under conventional Quality of Service (QoS) objective functions. Suboptimal and low complexity solutions are also proposed and evaluated. Finally, the durations of the relay-receive and relay-transmit phases are fixed, so that the interference induced by the other cells is stationary during a transmission interval. In that case, a low complexity algorithm is proposed. The performance of relayed CoMP-JP is compared to a relay-based transmission with uncooperating BSs. The results show the suitable application of
CoMP-JP in relay transmissions, as significant gains are obtained over the non-cooperating BSs relayed transmissions.

Once studied the performance of a homogeneous network (with only BSs) and a heterogeneous network with BSs and RSs for homogeneous traffic distribution in the macrocell, it is observed that make sense to deploy RSs for high inter site distances (ISD). However, it does not happen in a hotspot scenario where most of the users are near or inside the buildings (like a corporate scenario).

Therefore, in the third part of the project, a femto-relays tradeoff analysis is developed, where relays-based deployments are proposed to complement FAP-based deployments to improve indoor coverage in hotspot scenarios. Even though relay-based transmissions cannot compete with FAP-based transmissions, we can still benefit of deploying RSs to enhance system performance without increasing BS density and improve service to those users which are not attached to any FAP. To achieve the benefits given by the relay-based deployments, advanced MIMO access scheme based on CoMP are defined for BS-RS link, which provides significantly better downlink spectral efficiency and coverage than conventional CoMP BS-based schemes.

In order to minimize the interference between both networks, orthogonal subframes in TDD mode of LTE-A are assumed for RS transmissions and FAP transmission. The number of subframes assigned to each network is optimized following two different criterions, which depend on a design parameter to allow the operator one degree of flexibility to balance the resources towards relay users or the FAP users. Results allow for important conclusions: deploying relays allows improving the outage rate and the coverage in hotspot scenarios, moreover they can complement FAP-based deployments to improve the system cellular spectral efficiency in low density FAP deployments.
List of abbreviations & symbols

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<td>3G</td>
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<td>AMC</td>
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<td>Inter Site Distance</td>
</tr>
<tr>
<td>LOS</td>
<td>Line-Of-Sight</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>LTE-A</td>
<td>Advanced-Long Term Evolution</td>
</tr>
<tr>
<td>MAC</td>
<td>Media Access Control</td>
</tr>
<tr>
<td>MCS</td>
<td>Modulation and Coding Scheme</td>
</tr>
<tr>
<td>MC-CDMA</td>
<td>Multicarrier-Code Division Multiple Access</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>MUEE</td>
<td>Minimum Mean Square Error</td>
</tr>
<tr>
<td>MU</td>
<td>Multi-User</td>
</tr>
<tr>
<td>MU-MIMO</td>
<td>Multi-User Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>NLOS</td>
<td>Non-Line-Of-Sight</td>
</tr>
<tr>
<td>CoMP-JP</td>
<td>Network Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
</tr>
<tr>
<td>OFDM-TDMA</td>
<td>Orthogonal Frequency Division Multiplexing-Time Division Multiple Access</td>
</tr>
<tr>
<td>pdf</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
</tbody>
</table>
Access modes based on CoMP for relay transmissions in 4G systems

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB</td>
<td>Resource Block</td>
</tr>
<tr>
<td>RS</td>
<td>Relay Station</td>
</tr>
<tr>
<td>RSs</td>
<td>Relay Stations</td>
</tr>
<tr>
<td>Rx</td>
<td>Receiver</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal-to-Interference plus Noise-Ratio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise-Ratio</td>
</tr>
<tr>
<td>SR</td>
<td>Sum Rate</td>
</tr>
<tr>
<td>SU</td>
<td>Single-User</td>
</tr>
<tr>
<td>SU-MIMO</td>
<td>Single-User Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>SVD</td>
<td>Singular Value Decomposition</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>Tx</td>
<td>Transmitter</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UEs</td>
<td>Users Equipments</td>
</tr>
<tr>
<td>UL</td>
<td>UpLink</td>
</tr>
<tr>
<td>UMa</td>
<td>Urban Macro</td>
</tr>
<tr>
<td>UMi</td>
<td>Urban Micro</td>
</tr>
<tr>
<td>WiMAX</td>
<td>Worldwide Interoperability for Microwave Access</td>
</tr>
<tr>
<td>WSR</td>
<td>Weighted Sum Rate</td>
</tr>
<tr>
<td>ZF</td>
<td>Zero Forcing</td>
</tr>
</tbody>
</table>
**List of notations**

- **A**: Matrices: bold font and upper-case letters
- **a**: Vectors: bold font and lower-case letters
- **a**: Scalars: lower-case letters
- **I**: Identity matrix
- **0**: Zero matrix
- **(A)^T**: Transpose of matrix A
- **(A)^H**: Transpose conjugate of matrix A
- **(A)^{-1}**: Inverse matrix of matrix A. It satisfies: \( A^{-1} A = A A^{-1} = I \)
- **|A|**: Determinant of matrix A
- **|a|**: Modulus of scalar a
- **\|A\|**: Frobenious norm of matrix A
- **\|a\|**: Norm of vector a
- **Tr(A)**: Trace of matrix A
- **diag(A)**: Diagonal of matrix A. It returns a vector with the main diagonal of A: a = diag(A)
- **diag(a)**: Square diagonal matrix with the values of vector a in its diagonal: A = diag(a)
- **rank(A)**: Rank of matrix A. Is the minimum between the column rank and the row rank
- **kernel(A)**: Null space of matrix A. It returns a matrix containing vectors which satisfy Ax = 0
- **A \geq 0**: Matrix A is positive semi-definite
- **A_{ij}**: Element of matrix A located in the i-th row and the j-th column
- **A \otimes B**: Kronecker product of matrices A and B
- **max(a, b)**: Maximum between scalars a and b
- **min(a, b)**: Minimum between scalars a and b
- **(a)^{+}**: Maximum between scalar a and 0
- **ln(.)**: Natural logarithm
- **log(.)**: Logarithm base 10
- **log_{2}(.)**: Logarithm base 2
- **E{.}**: Expectation operation
- **Pr{.}**: Probability of event
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1 INTRODUCTION

1.1 Motivation and objectives

With the advent of new sophisticated terminals and bandwidth-demanding services, system designers are pushed towards the challenge of enhancing system spectral efficiency and providing homogeneous coverage for cellular networks. Future wireless system designs are expected to provide high cellular spectral efficiency (i.e., high aggregated cell data rate per unit of spectrum), since mobile data traffic has recently surged due to the availability of affordable data dongles, notebooks, tablet computers with third-generation (3G) radio modules, and smartphones with web-oriented user interfaces. Although 3G networks support this traffic growth, so far, more efficient wireless technology and novel deployment concepts are needed. Some research lines consider small cells and heterogeneous networks to provide the required capacity.

The design of such advanced network architectures is a challenging task. First of all, radio resources such as power and bandwidth are often scarce. Therefore, efficient resource allocation and network optimization are fundamental. Secondly, the wireless channel has its unique impairments such as fading and multi-path. Also, the mobiles sharing a common communication medium interfere with each other.

Next generation standards are already considering that conventional paradigms need to be rethought in a way able to exploit multiantenna capacity increase, shadowing diversity and pathloss break. In this respect, mature enabling technologies, like multiple-input multiple-output (MIMO) or full frequency reuse planning, are considered an integral part of the system; while other, like relay stations-based deployments and coordinated base stations transmissions, are part of ambitious study items. Leveraging on the advantages offered by the joint use of all these techniques, to improve performance and cost efficiency, is a challenge faced by IEEE 802.16m [1] and LTE-A [2][5].

LTE-A and mobile WiMAX are based on MIMO-orthogonal frequency-division multiplexing (OFDM) [12] to achieve improved spectral efficiency within one cell. However, inter-cell interference (i.e. interference between terminals of different cells) is still preventing these technologies from coming close to the theoretical rates for multi-cell networks.

One way to deal with inter-cell interference is through the coordination of base stations (BSs). The combination of MIMO-OFDM techniques in cellular systems with coordinated base stations (known as “Coordinated Multi-Point”, CoMP) is an attractive technique for future high-capacity cellular networks and, more important, to improve average cell edge throughput [13][14]. Third Generation Partnership Projects (3GPP) [2][3][4][5] distinguishes between the following categories of downlink base stations coordination:

- Coordinated scheduling/Coordinated beamforming (CoMP-CS/CB): User data is only available in one base station, the so-called serving base station, but user scheduling and beamforming decisions are dynamically coordinated among the cells in order to control and reduce the interference between different transmissions.
- Joint processing (CoMP-JP): User data to be transmitted to one user is simultaneously transmitted from multiple base stations of the network, which cooperate in order to work as a single transmitter with geographically separated transmit antennas. CoMP-JP has the benefit that, when used in conjunction with the Block Diagonalization and Zero-Forcing (BD-ZF) algorithm, it resolves the interference created by the strongest BS interferers.

This work is oriented to study the CoMP when joint processing is applied (which is also known as “Network-MIMO”). It is an efficient strategy, if channel state information at the transmitter (CSIT) is available, to combat inter-cell interference and jointly obtain full advantage of the multiplexing gains; as data symbol streams can be precoded in order to avoid interference
between the serving users and the channel matrix is unaffected by the rank of individual channels as each user is receiving from multiple BSs.

However, a very simple approach to increase network capacity is the reduction of cell sizes using additional radio access points (each one serving a smaller area), which if regular base stations are used is an expensive option. For that reason, heterogeneous networks (i.e. a cellular network where base stations can coexist with relay stations (RSs), femtocells (FAPs) or picocells) are part of ambitious studies to increase network capacity with lower infrastructure requirements [6][7]. Firstly, we focus on heterogeneous networks where BSs and RSs coexist and final users can be served by a direct transmission or a relay-based transmission. Secondly, in high density user’s deployments, it is also considered a heterogeneous network with BSs, RSs and FAPs.

On the one hand, relay transmissions is a promising approach that will have a large effect on a system’s functions and architecture [3]. While implementation details of full-duplex relays are still under investigation, relay-based enhancements in standards consider half-duplex relay operation, which incur a rate penalty as they require at least two timeslots to relay a message from source to destination. Optimizing the duration of the relay-receive and the relay-transmit phases is crucial to obtain high spectral efficiency (both for the One-Way Relay Channel and for the Two-Way Relay Channel [15][16]), which is a feasible feature of WiMAX and LTE-A.

In both cases, enhancing the capacity of the in-band wireless backhaul between source and relay (in our case, the BS–RS link) is essential. One of the solutions usually assumed is that RSs are placed in specifically planned positions above roof-top or in lampposts, ensuring line-of-sight (LOS) conditions in the BS–RS link, and hence reducing the pathloss and shadowing effects. The price to pay is twofold: the likely LOS propagating conditions also to other-cells BS, which will inject harmful interference, and the rank deficiency of the spatial channel when both BS and RS are equipped with more than one antenna. Both effects are detrimental to MIMO channel gains [18][19].

In this respect, CoMP-JP seems especially suited for in-band backhauling in relay transmissions in the downlink [13][14]. While coordination may be seen as an efficient way to combat the interference from neighboring cells, it also creates a virtual MIMO broadcast channel whose number of degrees of freedom is boosted (if compared to a conventional single-user MIMO under TDMA) and is hardly affected by the rank deficiency of single-user MIMO channels in LOS. It has been observed that CoMP-JP based on zero-forcing (BD–ZF) performs closely to dirty-paper coding [14] but, although its simplicity, it requires accurate channel knowledge from all involved links. CoMP-JP seems again to be appropriate for our problem thanks to the long channel coherence time of BS–RS links.

While both MIMO relaying and CoMP-JP have been extensively studied in the literature, little has been done to bond the benefits that can be obtained from both. The purpose of this project is to develop procedures that optimize some meaningful QoS-oriented function of the users’ rate, by jointly allocating resources to the BS-RS backhaul (MIMO precoders, transmission time and power) and to the RS-UE access links. Our focus will be operational adopting when necessary those assumptions that most reasonably reflect the practical scenarios under study in order to optimize the radio resource allocated to the wireless backhaul and the user access. We will jointly evaluate how the system can benefit of this design in terms of spectral efficiency and service homogeneity.

The optimization of duration of the relay-receive and the relay-transmit phases [15][16] is not convenient when considering multiple coordinated cells: if each group of coordinated cells adapts the duration of the transmission independently, the interference power observed in each transmission slot may be time-varying, a harsh and undesirable situation for the cellular system. Therefore, the evaluation of the CoMP-JP with in-band relaying for fixed duration of relay phases is necessary to guarantee the stationarity of other clusters interference within transmission frames. As compared to the case where the duration of the phases is optimized, the problem formulation is a particular case which can be solved by many power allocation strategies.
However, the optimal one can be found applying convex optimization techniques, and its solution has a significantly reduced complexity: the number of variables to be optimized turns out to be independent on the number of transmission modes, which makes the problem easier to multica
rrier systems.

On the other hand, femto access points deployments is being considered in different standards, such as IEEE 802.16m [1] and LTE-A [2][5], to enhance the system performance in terms of spectrum, energy and cost [8][9][10]. Currently, femtocells and relay stations or base stations are seen as isolated networks, competing for the resources available in the common spectrum band, at the cost of injecting interference to the whole system. However, we focus on evaluate the complementarities of both deployments by managing the interference in scenarios with a non-homogeneous traffic distribution (i.e. users non-uniformly distributed in the macrocell), where usually FAPs are deployed. The coexistence of both networks (FAP-based network and BS/RS-assisted network) is necessary since not all the users might have an FAP to attach with.

To evaluate the tradeoffs, we have to take into account that relay-based transmissions cannot compete with FAP-based transmissions due to the increased utilisation of radio resources arising from the half-duplexing of the RS and the for-free DSL bandwidth given to FAP (which allows achieving an enhanced transmission rate compared to a RS-assisted transmission). Moreover they are not comparable to serve indoor users, owing to the poorer indoor penetration of the outdoor RS.

However, we can still benefit of deploying RSs to enhance system performance without increasing BS density and improve service to those users which are not attached to any FAP. To achieve these benefits, advanced MIMO access scheme based on CoMP are defined for BS-RS link, which provides significantly better downlink spectral efficiency and coverage than conventional CoMP BS-based schemes. At low FAP densities, it seems a competitive solution for enhanced indoor services, whereas at medium and high FAP densities, they can become useless.

In order to minimize the interference between both networks, orthogonal subframes in TDD mode of LTE are assumed for RS transmissions and FAP transmission. The number of subframes assigned to each network can optimized following different criterions. We consider two: the first to have a fixed relation between spectral efficiency per user on each network and the second to have a fixed relation between the transmission time allocated per user on each network. Both criterions depend on a design parameter to allow the operator one degree of flexibility to balance the resources towards relay users or femto users.

1.2 Related publications

The combination of CoMP-JP and relay-assisted transmissions was studied in a paper published with the title: “Network-MIMO backhauling for QoS-constrained relay transmission” [20], which was accepted by the IEEE 2011 International Conference on Acoustics, Speech and Signal Processing (ICASSP 2011, Prague, May 2011).

Regarding the combination of CoMP-JP and relay transmissions with fixed duration of the phases, another paper was published with the title: “Network-MIMO for in-band relay transmission with relaying phases of fixed duration” [21], which was accepted by the 19-th European Signal Processing Conference (EUSIPCO 2011, Barcelona, September 2011).

With the same purpose and in order to adapt the duration of the phases to the LTE-A subframes durations, a contribution to the 3GPP LTE release 12 (TSG-RAN WG1, Athens, August 2011) was published, with the title: “Proposal of a CoMP study focused on relay-based networks” [22].
1.3 Overview

This document is structured as follows:

- Chapter 2 presents the modulation and multiple access modes that will be assumed and used in the project. Some relevant details are given from the OFDM modulation, and the multiple access modes that can be combined with it. The benefits of the implementation of MIMO aided OFDM are also presented.

- Chapter 3 describes the propagation channel model for mobile communications: the wireless and terrestrial propagation channel model. The characterization and details of the three effects that model the channel are provided: path loss, shadowing and fast fading, to finally model the MIMO fading channel.

- Chapter 4 presents the topology and the scenarios that will be developed in the project. Two topologies are detailed, depending if inter-macrocell interference is considered or not. Two scenarios are described, which differ by the homogeneity and the position of the deployed users: users can be outdoor and uniformly distributed in all the macrocell (which will be used in chapters 5 and 6) or they can be distributed non-homogeneously in the macrocell forming areas of high traffic demand (which will be used in chapter 7).

- Chapter 5 is focused on studying the CoMP-JP performance. Different types of coordination are presented and different precoding structures are evaluated. CoMP-JP performance is also studied in multicarrier transmissions, and it is addressed to the practical LTE-A implementations.

- Chapter 6 is oriented to study and evaluate the benefits of CoMP-JP and relay-assisted transmissions. A relay transmission with half-duplex terminals is detailed and the signal model for each link is developed. Firstly, the system is evaluated for variable durations of the relay-receive and relay-transmit phases; and some low complexity algorithms are proposed. Secondly, the system is evaluated for fixed durations of the phases to have stationary interference between macrocells; and a simple and efficiency algorithm is proposed to solve this case.

- Chapter 7 is devoted to study the tradeoffs in network deployments based on relay stations and femto access points. Relay-based deployments are proposed to complement FAP-based deployments for indoor coverage in a non-homogeneous traffic scenario. The access mode on each network is detailed and the evaluation of the joint FAP and RS-assisted network is performed at the system level.

Final conclusions and outlook are included in chapter 8.
2 MODULATION AND MULTIPLE ACCESS MODES

The choice of an appropriate modulation and multiple-access technique for mobile wireless data communications is critical to achieving good system performance. In particular, typical mobile radio channels tend to be time-dispersive, time-variant, frequency-dispersive and frequency-selective, and this has generated interest in multicarrier modulation.

In general, multicarrier schemes subdivide the used frequency-selective channel bandwidth into a number of parallel non-frequency-selective subchannels (i.e. subchannels have a spectrally-flat gain) as it is shown in Figure 1. This has the advantage that the receiver can easily compensate for the subchannel gains individually in the frequency domain.

![Figure 1: Multicarrier modulation scheme with frequency-selective channel.](image1)

Orthogonal Frequency Division Multiplexing (OFDM) is a special case of multicarrier transmission which is highly attractive for implementation. In OFDM, the non-frequency-selective subchannels are overlapping but orthogonal. This avoids the need to separate the carriers by means of guard-bands, and therefore makes OFDM highly spectrally efficient. Moreover, it allows a low-complexity receiver implementation – as data symbols can be recovered using FFT operation –, which makes OFDM attractive for high-rate mobile data transmission such as the LTE and LTE-A downlink.

The following section 2.1 provides the details of the OFDM modulation and section 2.2 the multiple access modes that can be combined with it. In section 2.3, we describe the benefits of the use of MIMO technique combined with OFDM modulation, which allows an additional multiple access mode: Spatial Division Multiple Access (SDMA).

2.1 Orthogonal Frequency Division Multiplexing

OFDM compacts the spectrum selecting \( N \) subcarrier frequencies so as each subchannel is orthogonal to the others on the symbol time span:

\[
\omega_i = \frac{2\pi}{\text{FFT}} i, \quad i = -\frac{N}{2}, \ldots, \frac{N}{2} - 1
\]

\[T_{\text{FFT}} = N T_{\text{sampling}}\]  

(1)

The OFDM signal used in LTE-A is composed of up to 2,048 different subcarrier frequencies, spaced 15 kHz.

The \( N \) subchannels overlap in frequency, as it is shown in Figure 2. In perfect synchronization conditions, at the instant of sampling a certain subcarrier frequency, the other subcarrier frequencies have a value equal to zero and, consequently, orthogonality is maintained between all subcarrier frequencies. To further reduce out-of-band radiation, some of the highest frequency subcarriers are not modulated. The zero-frequency carrier is not modulated either, to avoid symbols loss due to base band DC uncoupling at the receiver.
Access modes based on CoMP for relay transmissions in 4G systems

In OFDM it is possible to use different modulations (e.g. QPSK or 16-QAM) on each subcarrier, thanks to the use of Adaptive Modulation and Coding (AMC). AMC allows adapting the modulation and coding scheme (MCS) and power allocation to the different channel gains over the different sub-channels present in the frequency selective channels (see Figure 1), and thus some sub-carriers can carry higher data-rates than others. In this way, the frequency domain variations of the multipath channel are used effectively so as to obtain advantages such as higher data rates and lesser transmitted power when compared with uniformly loaded system. AMC needs knowledge of the multipath channel’s characteristics at the transmitter to adapt the modulation and coding on each subcarrier; in OFDM systems it is obtained through the feedback mechanisms which are also being considered in LTE.

In time domain, the OFDM signal is structured as it is shown in Figure 3. A guard period ($T_g$) is created at the beginning of each OFDM symbol to deal with multipath and removing the impact of ISI. This guard period is obtained by means of a Cyclic Prefix (CP), which is generated by duplicating the last samples of the present symbol (represented with dark gray colour in Figure 3). To avoid ISI completely, the CP length must be longer than the longest channel impulse response ($\tau_{\text{max}}$) to be supported:

$$\tau_{\text{max}} < T_g$$

Moreover, a window period ($T_{\text{win}}$) is created between each OFDM symbol to reduce out-of-band radiation and prevent ripple in frequency resulting from the side-lobes of the “pulse shaping” (or “sync-function”) due to the time windowing.

Figure 3: OFDM signal in time.

Since the waveforms associated to each subcarrier are orthogonal over the OFDM symbol period ($T_{\text{FFT}}$), the symbols can be exactly and independently recovered from the transmitted signal if there are no timing and carrier frequency errors.
2.2 **OFDM multiple access modes**

Various multiple access schemes can be combined with OFDM transmission. They include: OFDM-Time Division Multiple Access (OFDM-TDMA), Orthogonal Frequency Division Multiple Access (OFDMA) and Multicarrier-Code Division Multiple Access (MC-CDMA).

In OFDM-TDMA, time is divided in multiples of OFDM symbols and they are used to separate the transmissions of multiple users as shown in Figure 4. This means that all the used subcarriers are allocated to a single user for a finite number of OFDM symbol periods.

In OFDMA systems both time and frequency resources can be employed to separate the multiple user signals. Groups of OFDM symbols and groups of subcarriers are the units used to separate the transmission to/from multiple users. In Figure 4, the time-frequency view of typical OFDMA signal is shown.

In MC-CDMA systems a data symbol is sent on multiple subcarriers by using a spreading code, which is different for multiple access users. Multiple user signals overlap in time and frequency domain but they can be separated at the receiver by using the knowledge of the spreading codes. Thus, MC-CDMA can be considered as a combination of OFDM and CDMA schemes resulting in benefits due to both of these approaches.

![Figure 4: Time-frequency of OFDM-TDMA signal (left) and OFDMA signal (right).](image)

In this work, the transmission access mode considered for the downlink transmission is OFDM-TDMA, which is a particular case of the access mode used in LTE-A downlink transmission [12], OFDMA. In section 2.3 we will see that, thanks to the use of MIMO technique -which allows space division multiple access-, the OFDM-TDMA access mode turns out to be similar to OFDMA when applying power loading algorithms.

2.3 **Multiple-Input Multiple-Output OFDM**

The employment of multiple antennas at both the transmitter and the receiver, which is widely referred to as the Multiple-Input Multiple-Output (MIMO) technique, constitutes a cost-effective approach to get high-throughput wireless communications. A MIMO system is capable of exploiting both transmitter and receiver diversity as parallel data streams can be delivered to the user, hence improving robustness of wireless communications. Furthermore, with the advent of multiple antennas, it is possible to jointly process/combine the multi-antenna signals and thus improves the system’s spectral efficiency and homogeneity.

MIMO techniques can be combined with any modulation or multiple access schemes. Even so, recent research suggests that the implementation of MIMO aided OFDM is more efficient in terms of spectral efficiency, as a benefit of the straightforward matrix algebra invoked for processing the MIMO OFDM signals [25].

The use of MIMO technique allows Spatial Division Multiple Access (SDMA), which exploits the spatial dimension of the system and enables multiple users to simultaneously share the same bandwidth in different geographical locations. More specifically, it allows the
identification of the individual users in the spatial dimension, even when they are in the same time/frequency/code domains; thus increasing the system spectral efficiency.

Therefore, when considering the OFDM-TDMA or OFDMA signals (see Figure 4), multiple users can be served simultaneously in a given time and frequency. In case that channel state information at the transmitter (CSIT) is available, we can adapt the power allocated to each user on each time and frequency band, in order to take advantage of the propagation channel conditions. For example, for a specific user, more power would be allocated to those frequency bands with good channel propagation conditions, while the power allocated to the frequency bands with bad channel propagation conditions would be zero. This technique is known as “power loading”. By this way, the users -or transmission modes, when considering multiple receive antennas- served on each frequency band can be different, and it allows the OFDM-TDMA access mode to be similar to the OFDMA access scheme when applying power loading algorithms.

MIMO-OFDM is used in LTE-A to achieve improved spectral efficiency within one cell. However, inter-cell interference (i.e. interference between terminals of different cells) is still preventing these technologies from coming close to the theoretical rates for multi-cell networks. There are two fundamental ways to deal with inter-cell interference:

- coordination of base stations to avoid interference,
- coherent base station cooperation to exploit constructively the interference.

The combination of MIMO-OFDM techniques in cellular systems with coordinated base stations is known as “Network MIMO” or “Coordinated Multi-Point Transmission - CoMP” [4]. CoMP is able to deal with the inter-cell interference and jointly to improve the cellular spectral efficiency. For that reason, it is an attractive technique for future high-capacity cellular networks [13][14].

Conceptually, in chapters 5 and 6, we extend single-cell MIMO techniques, such as multi-user MIMO (MU-MIMO), to multiple coordinated cells in order to exploit the advantages of the coordination and cooperation of multiple base stations.
3 PROPAGATION CHANNEL MODEL

In mobile wireless downlink data transmission the signal received in the receiver is always affected by the propagation channel. For terrestrial environments, the propagation effects are divided into three distinct types:

- the path loss ($P_l$),
- the slow variation due to shadowing and scattering ($S$),
- and the rapid variation in the received signal -also named fast fading- due to multipath effects ($g$).

Those three effects model the losses over the received signal in the receiver by the following relation:

$$h = \sqrt{P_l} \times \sqrt{S} \times g$$  \hspace{1cm} (2)

Next sections provide the details of the channel models for the terrestrial component, including the path loss models in section 3.1, the shadowing variation in section 3.2, and the fast fading characterization in section 3.3. Section 3.4 presents the channel model of a MIMO system, taking into account all the propagation effects.

3.1 Path loss

Path loss is the effect characterized by the reduction in the power received due to the distance between the transmitter and the receiver. In free space propagation it is modelled as:

$$P_{free}[\text{dB}] = \left(\frac{4\pi d}{\lambda}\right)^2$$

where $d$ is the distance between the transmitter and the receiver and $\lambda$ is the wavelength, related to the carrier frequency: $\lambda = c / f$.

When considering terrestrial propagation, we have to take account of many other factors, such as reflection, refraction, diffraction, aperture-medium coupling loss and absorption. In general, for terrestrial propagation, path loss is characterized as follows:

$$P_l[\text{dB}] = \beta \left(\frac{d}{d_o}\right)^{-\rho}$$  \hspace{1cm} (3)

where $\beta$ is the propagation constant, related to the carrier frequency: $\beta = 2\pi f / c$, $d_o$ is the reference distance and $\rho$ is the propagation exponent, which depends on the environment: $\rho = 2$ for free space, $\rho = 2 - 6$ in outdoor and indoor environments.

As (3) depends on some variable parameters ($\rho$ and $d_o$), path loss models for the different terrestrial propagation scenarios have been developed based on results from the literature. Specifically, for each channel propagation conditions, we will use the following models:

- Base station (BS) – Relay station (RS) link:
  - B5a LOS for Urban/Suburban/Rural environments from Winner II [23]
  - C1 NLOS for Urban/Suburban environments from Winner II [23]
- Base station (BS) – Outdoor user equipment (UE) link:
  - C2 LOS/NLOS for Urban environments from Winner II [23]
- Relay station (RS) – Outdoor user equipment (UE) link:
  - Urban Micro (UMi) LOS/NLOS from ITU [3]
Access modes based on CoMP for relay transmissions in 4G systems

- Base station (BS) – Indoor user equipment (UE) link:
  - NLOS building penetration model from COST231 [11]
- Relay station (RS) – Indoor user equipment (UE) link:
  - C4 NLOS from ITU [3]
- Femto access point (FAP) – Outdoor user equipment (UE) link:
- Femto access point (FAP) – Indoor user equipment (UE) link:
  - building penetration model from COST231 [11]

Figure 5 illustrates the path loss model used on each link of each propagation channel. RS are outdoor and FAP are always indoor, even they can serve both outdoor and indoor users.

![Figure 5: Path loss model on each link.]

The explicit details of each path loss model and the LOS/NLOS probabilities can be found in Annex A.

3.2 Shadowing

Shadowing is the effect characterized by the slow variation in the power received owing to the different obstacles that appear between transmitter and receiver.

Shadowing will be assumed Gaussian in logarithmic scale

$$10\log_{10} S \sim N(0, \sigma_S^2)$$

and its variance depends on distance between transmitter and receiver, propagation scenario and LOS/NLOS situation, by the following way:

$$\sigma_S^2 = \sigma^2 \left( 1 - \exp \left( -\frac{|P_t - P_{free}|}{4} \right) \right) + 1.5$$

$$\sigma^2 = 3, \ldots, 12 \text{dB}$$

$$\sigma^2$$ varies with the propagation scenario and the LOS/NLOS situation. Its exact values are detailed in Annex A for each propagation scenario, path loss model and LOS/NLOS model.

Path loss and shadowing effects depend on whether the location is LOS or NLOS – this probability is distance dependent, while the fast fading effect is less correlated to the distance between transmitter and receiver.

3.3 Fast fading

Fast fading refers to the fast variation in the power received due to the multipath propagation. In wireless systems, there are a large number of obstacles between transmitter and
receiver, each one reflecting the signal transmitted by the transmitter. Each signal replica arrives at the Rx affected by a delay, a Doppler shift and a random complex amplitude; and the received signal is the superposition of all those signal replicas -which can produce constructive or destructive losses-.

To quantify the fading effect, coherence time and the coherence bandwidth are defined as the time interval and the bandwidth where the channel can be considered constant, respectively:

\[
T_c \approx \frac{1}{4f_d} \quad \text{and} \quad B_c \approx \frac{1}{2\pi \tau_o}
\]  

where \( f_d \) is the Doppler frequency (which is proportional to the user’s velocity: \( f_d = v/\lambda \)), and \( \tau_o \) is the maximum delay of the received replicas at the receiver.

Channels can be classified as time-selective and/or frequency-selective, when coherence time and coherence bandwidth defined in (6) are compared to the time duration \( T \) and the bandwidth \( B \) of the signals transmitted, respectively. The channel is time-selective when it can be considered constant in a lower time interval than the duration of the signal transmitted. The channel is classified as frequency-selective when it is not constant in the bandwidth of the transmitted signal. Table 1 summarizes the classification of the channels, depending on the parameters defined in (6).

### Table 1: Channels classification

<table>
<thead>
<tr>
<th>Channel Type</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-selective channel</td>
<td>( T_c &lt; T )</td>
</tr>
<tr>
<td>Invariant channel</td>
<td>( T_c &gt; T )</td>
</tr>
<tr>
<td>Frequency-selective channel</td>
<td>( B_c &lt; B )</td>
</tr>
<tr>
<td>Flat channel</td>
<td>( B_c &gt; B )</td>
</tr>
</tbody>
</table>

Channels affected by multipath propagation have different parts of the transmitted signal spectrum attenuated differently, and thus resulting in frequency-selective channels. Moreover, if the user is not static, the resulting channel will be time-selective. Therefore, in general, we will consider that mobile wireless channels are selective in time and frequency.

On the one side, thanks to the OFDM modulation described in 2.1, we can combat the frequency selectivity; as the total channel bandwidth (corresponding to a frequency-selective channel) is divided into \( N \) flat subchannels (see Figure 1).

On the other side, time selectivity can be combated with the multiple access mode TDMA, as we can adapt the time interval allocated to each user accordingly to its velocity in such a way that the channel is invariant in the transmission interval.

Therefore, when combining OFDM and TDMA we can strongly combat with frequency-selective and time-variant channels.

### 3.4 MIMO fading channel

Let us consider a point-to-point MIMO system between one transmitter with \( n_T \) transmit antennas and one receiver with \( n_R \) receive antennas, see Figure 6. If we assume a non-frequency selective (flat) channel, the signal at the receiver is given by:

\[
y = H x + n = \begin{pmatrix} h_{11} & h_{12} & \cdots & h_{1n_T} \\ h_{21} & h_{22} & \cdots & h_{2n_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{n_T1} & h_{n_T2} & \cdots & h_{n_Tn_T} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_{n_T} \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \\ \vdots \\ n_{n_T} \end{pmatrix}
\]  

(7)
where \( y \) is the \( n_R \times 1 \) signal received at the receiver, \( x \) is the \( n_T \times 1 \) signal transmitted by transmitter, \( n \) is the additive white Gaussian noise (AWGN) at the receiver containing \( n_R \) circularly symmetric complex Gaussian components with zero mean and variance \( E[|n|^2] = \sigma_r^2 I \), and \( H \) is the \( n_R \times n_T \) channel matrix containing the channel gain between each transmit antenna and each receive antenna. The channel coefficients are constant along the transmission time.

Hence, the transmission rate is upper-bounded by the following expression [17]:

\[
R \leq B \log_2 \left( 1 + \frac{P_t}{\sigma_n^2 B} \|HH^H\| \right) \approx B \min(n_r, n_R) \log_2 \left( 1 + \frac{P_t}{\sigma_n^2 B n_r} \right)
\]

(8)

where \( P_t \) is the power available at the transmitter and \( B \) is the total bandwidth of transmission.

From expression (8) we can define the Degrees of Freedom (DoF) of the point-to-point MIMO system as the maximum number of independent messages transmitted in one channel use:

\[
\text{DoF} = \min(n_r, n_R)
\]

(9)

It can be observed that the transmission rate scales with the DoF (i.e. with the minimum number of transmit and receive antennas). Thus, makes the MIMO systems using OFDM modulation (to convert a frequency selective channel into flat subchannels, which is the first assumption to express (7)) a system very robust to fast fading, due to the spatial multiplexing.

Therefore, the MIMO channel can be modelled as a Rayleigh channel correlated in transmission and reception, without the fast fading effect, with the following expression extrapolated from (2):

\[
H = \sqrt{P_t} \times S \times \left( R^{1/2}_r G R^{1/2}_t \right)
\]

(10)

where \( R^{1/2}_r \) is the spatial correlation between receive antennas, \( R^{1/2}_t \) is the spatial correlation between transmit antennas and \( G \) is a matrix with Gaussian components with zero mean and variance \( E[GG^H] = I \). As it can be observed in (10), fast fading is not included.

MIMO systems are robust to fast fading, even they are very sensitive to path loss and shadowing effects. In this respect, as we will see in chapter 6, deploy terminals acting as repeaters can help to combat both effects.

Figure 6: MIMO system architecture.
4 SYSTEM TOPOLOGY AND SCENARIOS

This chapter details the topology and the scenarios considered in the project. In the simulations results the topology described next is used, although in chapters 5 and 6 the nomenclature is extended to the general case. Section 4.1 details the cell deployment and two different topologies, which will be deployed and evaluated, depending on the external interference. Section 4.2 presents two different scenarios depending on the user’s position: in the first scenario users are placed outdoor and homogeneously distributed in the macrocell, and on the second scenario users can be placed outdoor or indoor but with a non-homogeneous distribution. For each scenario the simulation parameters are detailed.

4.1 Cell deployment

In cluster cellular systems the most common and used deployment is the hexagonal deployment, which allow tessellation similar to the circle area. With this deployment and in order to allow coordination between base stations (i.e. exchange of control plane information between the BSs), each BS is equipped with 3 linear antennas arrays -each one used to serve one cell- and a deployment with converging cells is considered. Figure 7 shows the deployment considered with converging cells. The coordinated area (delimited by the green line) is composed of three cells covered by three BSs, and it will be called macrocell.

![Figure 7: Hexagonal deployment with converging cells.](image)

The hexagonal topology with converging cells has the benefit that, when used in conjunction with the BD-ZF (Block Diagonalization and Zero-Forcing) algorithm, it resolves the inter-cell interference created by the strongest BSs interferers.

In order to distinguish the interference coming from the cells of the coordinated area and the interference from the cells out of the coordinated area, we define three different types of interference:

- *intra-cell interference*: interference between terminals belonging to the same cell.
- *inter-cell interference*: interference between terminals of different cells belonging to the same macrocell.
- *inter-macrocell interference*: interference between terminals of different macrocells.

In LTE-A full frequency reuse (i.e. frequency reuse equal to 1) is assumed to simplify network deployments; even it creates significant inter-cell and inter-macrocell interference at the cell edge. Therefore, in order to evaluate and compare how the inter-macrocell interference affects when we use full frequency reuse, two different topologies are deployed and evaluated depending if we consider an isolated macrocell (Topology A) or a multiple-macrocell deployment (Topology B).
4.1.1 Topology A: Single macrocell deployment

The performance of an isolated macrocell is evaluated. Inter-cell interference is created in the coordinated area but inter-macrocell interference is not considered. Topology A can be observed in Figure 8, when using and not Relay Stations.

Figure 9 shows the deployment considered for a single macrocell when several relays and several FAP areas are deployed over the coordinated area. Each FAP area is composed of two buildings. In the simulation results, two FAP areas and two RS are deployed per cell, RS are positioned in the centre of each FAP area, and the density of FAPs varies with the deployment.

![Figure 8: Topology for a single macrocell deployment with relay stations.](image)

![Figure 9: Topology for a single macrocell deployment with FAP areas and relay stations.](image)

4.1.2 Topology B: 19-macrocell deployment

The performance of a macrocell is evaluated in a macrocell deployment with 19 macrocells when full frequency reuse is considered. Since all the macrocells deployed use the same frequency bands, inter-cell interference and inter-macrocell interference are created. Therefore, the interference induced by the closest 18 macrocells has to be considered. In a hexagonal deployment, those 18 macrocells are distributed in the following way: 6 macrocells in the first closest level and 12 macrocells in the second level. The interference received from the third
level macrocell is considered to be lower enough compared to the interference from the macrocells of level 1 and 2.

Topology B is simplified in Figure 10 for 7 macrocells (6 macrocells in the first closest level, which create interference over the coordinated area). The strongest inter-macrocell interference is represented with pink lines.

Figure 10: Topology for a 7-macrocell deployment with inter-macrocell interference over the DL coordinated area.

4.2 Scenarios

The detailed topologies A and B can be applied to different propagation scenarios. In particular, we consider two scenarios depending on the distribution of the users in the macrocell. Users can be placed outdoor or indoor and they can be distributed homogeneously or non-homogeneously in all the macrocell. In this project, the scenarios considered are:

- **Outdoor homogeneous**: users are placed outdoor and uniformly distributed in the macrocell.
- **Outdoor/Indoor Hotspot**: users are placed outdoor and indoor and they are distributed non-homogeneously in the macrocell.

4.2.1 Outdoor homogeneous scenario

The outdoor homogeneous scenario models a typical residential area, where users are supposed to be distributed homogeneously in all the macrocell. Then, two types of environments can be found: urban environments or suburban environments.

In the urban environments it is assumed that a high number of users need to be served simultaneously, and then, the Inter Site Distance (ISD) is considered to be equal to 500 meters, as the specified in the LTE-Advanced for this scenario. The simulation results are also taken for higher ISD, which will imply a lower cost in infrastructure.

In the suburban environments it is supposed that a lower number of users need to be served simultaneously, and then a lower inversion is normally done in telecommunications infrastructure. In other words, the ISD is higher due to the lack of cable infrastructure (which is
needed to communicate BSs). The commonly used ISD for this scenario is 1732 meters. For the simulations results, we also consider ISD from 1000m to 3000m. In those environments, it makes sense to deploy Relay Stations (RSs) terminals to increase the system performance without the need of a cable infrastructure, as the RS is wirelessly connected to the radio-access network via a BS. Relaying transmission is suitable for those environments as it is a tool to improve the cell-edge throughput, the coverage of high data rates, group mobility, temporary network deployment and/or to provide coverage in new areas.

The outdoor homogeneous scenario will be developed for chapters 5 and 6, where BSs and RSs can coexist in the network.

### 4.2.2 Outdoor/Indoor Hotspot scenario

The outdoor and indoor hotspot scenario defines a typical corporate scenario, which models a dense-urban business area where many corporations are their sites. More specifically, users are usually placed near or inside the buildings. So, users are distributed non-uniformly or in the macrocell. As a characterization of the dense-urban environments, a high density user deployment is considered.

Due to the high amount of data traffic (which cannot be served by the base stations) and the hotspot scenario, in these environments it makes sense to deploy femto access points (FAPs) inside the buildings to improve the indoor coverage. However, not all the indoor users might have a FAP to associate with, and then, deploy RS is a low-cost way to improve the indoor coverage and the service to those users without a serving FAP.

The outdoor and indoor hotspot scenario will be developed in chapter 7, where BSs, RSs and FAPs are deployed. In this scenario, RS-based deployments are proposed to complement FAP-based deployments for indoor coverage.

### 4.2.3 Scenarios comparison

To clear up, Table 2 summarizes the configuration and deployment parameters for Outdoor homogeneous scenario and Outdoor/Indoor hotspot scenario (also remarking the differences between urban and suburban environments for the outdoor homogeneous).

| Table 2: Outdoor homogeneous scenario and Outdoor/Indoor hotspot scenario comparison |
|---------------------------------|---------------------------------|
| Users position                  | Outdoor homogeneous scenario    | Outdoor/Indoor Hotspot scenario |
| Users deployment                | Homogeneously: uniformly in all macrocell | Non-homogeneously: inside/near to buildings |
| Environment                     | Urban/Suburban                  | Dense urban                      |
| Infrastructure                  | Urban: BS                       | BS and FAP                      |
|                                 | Suburban: BS and RS             | BS, RS and FAP                  |
| ISD                             | Urban: 500 m.                   | 1000 m.                          |
|                                 | Suburban: 1732 m.               |                                  |
| alternative ISD                 | Urban: 500 - 2000 m.            |                                  |
|                                 | Suburban: 1000 - 3000 m.        |                                  |

Figure 12 shows the user’s deployment for a given realization in Outdoor homogeneous scenario. Figure 11 displays the user’s deployment in Outdoor/Indoor hotspot scenario. Rectangles in Figure 11 identify the buildings with several sites and floors, where most of the users are placed nearby.
RS position depends on the scenario: for outdoor/indoor hotspot they will be placed in the centre of each FAP area, and for outdoor homogeneous they will be placed uniformly on each sector.

**Figure 11:** User’s deployment in Outdoor homogeneous scenario.

**Figure 12:** User’s deployment in Outdoor/Indoor hotspot scenario.

### 4.2.4 Simulation parameters for outdoor homogeneous scenario

For outdoor homogeneous scenario, a radio access network based on LTE-A specifications [5] is performed. $B=3$ BSs and a total of $R=6$ RSs are deployed on the macrocell. All the RSs are at the same distance $d$ to their associated BS, equal to 60% of the cell radius for topology A and 65% of the cell radius for topology B (which has been experimentally found to be the optimal RS position in the macrocell). On each user deployment, $M=6$ users are dropped uniformly in the macrocell arrangement, one assigned to each RS. Table 3 gives an overview of all relevant simulation parameters.
Table 3: Overview of simulation parameters for outdoor homogeneous user deployment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central frequency</td>
<td>2 GHz</td>
</tr>
<tr>
<td>Channel bandwidth and duplex method</td>
<td>20 MHz in TDD, 10 MHz in FDD</td>
</tr>
<tr>
<td>Macrocell Order</td>
<td>B=3</td>
</tr>
<tr>
<td>Inter Site Distance (ISD)</td>
<td>500, 1000, 1500, 2000, 2500, 3000 m</td>
</tr>
<tr>
<td>Number of sectors</td>
<td>3</td>
</tr>
<tr>
<td>Number of relays per sector</td>
<td>R=2</td>
</tr>
<tr>
<td>Sectors configurations</td>
<td>Convergent sectors</td>
</tr>
<tr>
<td>Antenna height BS</td>
<td>25 m</td>
</tr>
<tr>
<td>Antenna height RS</td>
<td>10 m</td>
</tr>
<tr>
<td>Antenna height UE</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Tx Power BS</td>
<td>46 dBm</td>
</tr>
<tr>
<td>Tx Power RS</td>
<td>37 dBm</td>
</tr>
<tr>
<td>Noise spectral density</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Pathloss models</td>
<td>BS to RS: B5a LOS and C1 NLOS Winner II</td>
</tr>
<tr>
<td></td>
<td>BS to UE: C2 (UMa) Winner II with 25m Tx antenna height</td>
</tr>
<tr>
<td></td>
<td>RS to UE: ITU UMi with 10m Tx antenna height</td>
</tr>
<tr>
<td>MIMO channel</td>
<td>LOS and NLOS angular dispersion used</td>
</tr>
<tr>
<td>Shadowing &amp; Fast Fading</td>
<td>Distance-dependent shadowing, from Winner</td>
</tr>
<tr>
<td>Shadowing standard deviation</td>
<td>BS to RS: B5a LOS and C1 NLOS Winner II</td>
</tr>
<tr>
<td></td>
<td>BS to UE: ITU UMa / C2 Winner II</td>
</tr>
<tr>
<td></td>
<td>RS to UE: ITU UMi</td>
</tr>
<tr>
<td>Antenna array/elements at BS</td>
<td>ULA / 4 -12</td>
</tr>
<tr>
<td>Max. number of beams</td>
<td>n_B=4</td>
</tr>
<tr>
<td>Antenna elements at RS</td>
<td>n_R=2</td>
</tr>
<tr>
<td>Antenna elements at UE</td>
<td>n_M=1</td>
</tr>
<tr>
<td>BS antenna gain</td>
<td>17 dBi</td>
</tr>
<tr>
<td>RS antenna gain</td>
<td>5 dBi</td>
</tr>
<tr>
<td>Noise factor at BS and RS</td>
<td>7</td>
</tr>
<tr>
<td>Noise figure at UE</td>
<td>9 dB</td>
</tr>
<tr>
<td>Feeder loss</td>
<td>0 dB</td>
</tr>
<tr>
<td>Body loss at UE</td>
<td>0 dB</td>
</tr>
<tr>
<td>Coding loss</td>
<td>4 dB</td>
</tr>
<tr>
<td>Cable loss at BS/RS/UE</td>
<td>2 dB / 0 dB / 0 dB</td>
</tr>
<tr>
<td>Number of resource blocs</td>
<td>100</td>
</tr>
</tbody>
</table>

4.2.5 Simulation parameters for outdoor/indoor hotspot scenario

For outdoor/indoor homogeneous scenario, the simulation parameters are different from the outdoor homogeneous scenario (in section 4.2.4) since a corporate scenario in a hotspot and dense-urban environment is considered. A deployment with several corporate buildings is developed; each group of two buildings and the streets between them perform a FAP area, in which all the traffic and the femto access points (FAPs) will be placed. For that reason, user deployment parameters are taken from [8] and the radio access network is performed following the LTE-A specifications [5]. B=3 BSs and one RS per FAP area is deployed. RSs are positioned in the centre of each FAP area. On each user deployment, in average M=75 users are dropped inside the FAP areas. Table 4 gives an overview of all relevant simulation parameters.
Table 4: Overview of simulation parameters for outdoor/indoor hotspot user deployment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central frequency</td>
<td>2 GHz</td>
</tr>
<tr>
<td>Channel bandwidth and duplex method</td>
<td>20 MHz in TDD, 10 MHz in FDD</td>
</tr>
<tr>
<td>Macrocell Order</td>
<td>B=3</td>
</tr>
<tr>
<td>Inter Site Distance (ISD)</td>
<td>1000 m</td>
</tr>
<tr>
<td>Number of sectors</td>
<td>3</td>
</tr>
<tr>
<td>Sectors configuration</td>
<td>Convergent sectors</td>
</tr>
<tr>
<td>FAP area composition</td>
<td>2 buildings with several floors, 3 streets</td>
</tr>
<tr>
<td>Number of offices on each floor</td>
<td>10</td>
</tr>
<tr>
<td>FAP office size</td>
<td>10m x 10m</td>
</tr>
<tr>
<td>FAP office height</td>
<td>3 m</td>
</tr>
<tr>
<td>Street weight</td>
<td>10 m</td>
</tr>
<tr>
<td>Antenna height BS</td>
<td>32 m</td>
</tr>
<tr>
<td>Antenna height RS</td>
<td>10 m</td>
</tr>
<tr>
<td>Antenna height FAP</td>
<td>1 m</td>
</tr>
<tr>
<td>Antenna height UE</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Tx Power BS</td>
<td>46 dBm</td>
</tr>
<tr>
<td>Tx Power RS</td>
<td>37 dBm</td>
</tr>
<tr>
<td>Tx Power FAP</td>
<td>20 dBm</td>
</tr>
<tr>
<td>Noise spectral density</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Pathloss models</td>
<td>BS to RS: B5a LOS and C1 NLOS Winner II</td>
</tr>
<tr>
<td></td>
<td>BS to UE outdoor: C2 (UMa) Winner II</td>
</tr>
<tr>
<td></td>
<td>BS to UE indoor: Dense urban indoor</td>
</tr>
<tr>
<td></td>
<td>RS to UE outdoor: ITU UMi with 10m Tx antenna height</td>
</tr>
<tr>
<td></td>
<td>RS to UE indoor: C4 Winner II</td>
</tr>
<tr>
<td></td>
<td>FAP to UE: FAP-UE indoor/outdoor from [8]</td>
</tr>
<tr>
<td>MIMO channel</td>
<td>LOS and NLOS angular dispersion used</td>
</tr>
<tr>
<td>Shadowing &amp; Fast Fading</td>
<td>Distance-dependent shadowing, from Winner</td>
</tr>
<tr>
<td>Shadowing standard deviation</td>
<td>BS to RS: B5a LOS and C1 NLOS Winner II</td>
</tr>
<tr>
<td></td>
<td>BS to UE: ITU UMa / C2 Winner II</td>
</tr>
<tr>
<td></td>
<td>RS to UE: ITU UMi / C4 Winner II</td>
</tr>
<tr>
<td></td>
<td>FAP to UE: FAP-UE from [8]</td>
</tr>
<tr>
<td>Antenna array/elements at BS</td>
<td>ULA / 4 -12</td>
</tr>
<tr>
<td>Max. number of beams</td>
<td>nR=4</td>
</tr>
<tr>
<td>Antenna elements at RS</td>
<td>nR=2</td>
</tr>
<tr>
<td>Antenna elements at FAP</td>
<td>nF=2</td>
</tr>
<tr>
<td>Antenna elements at UE</td>
<td>nM=2</td>
</tr>
<tr>
<td>BS antenna gain</td>
<td>14 dBi</td>
</tr>
<tr>
<td>RS antenna gain</td>
<td>5 dBi</td>
</tr>
<tr>
<td>FAP antenna gain</td>
<td>5 dBi</td>
</tr>
<tr>
<td>Noise figure at BS and RS</td>
<td>5 dB</td>
</tr>
<tr>
<td>Noise figure at FAP</td>
<td>8 dB</td>
</tr>
<tr>
<td>Noise figure at UE</td>
<td>9 dB</td>
</tr>
<tr>
<td>Feeder loss / Body loss at UE</td>
<td>0 dB / 0 dB</td>
</tr>
<tr>
<td>Penetration loss due to buildings</td>
<td>10 dB</td>
</tr>
<tr>
<td>Coding loss</td>
<td>4 dB</td>
</tr>
<tr>
<td>Cable loss at BS/RS/FAP/UE</td>
<td>0 dB / 0 dB / 0 dB / 0 dB / 0 dB</td>
</tr>
<tr>
<td>Number of resource blocs</td>
<td>100</td>
</tr>
</tbody>
</table>
5 COORDINATED MULTIPONT JOINT PROCESSING

CoMP-JP is a MIMO-OFDM system based on the coordination and cooperation of the base stations (BSs), which is highly attractive to deal with the inter-cell interference and jointly improve the cellular spectral efficiency. This chapter is focused on studying the CoMP-JP performance. We are going to detail next the signal model at the transmitter and the receiver. Section 5.1 describes different types of coordination between the BSs, which model different precoding matrices. Section 5.2 studies different precoding structures in order to maximize the user’s transmission rate. The maximization problem is shown to be convex, and its optimal solution is given and the whole system is evaluated. In section 5.3, CoMP-JP is developed for multicarrier transmissions. And, finally, section 5.4 is oriented to achieve practical LTE-A implementations.

Let us adopt a downlink transmission setup where $B$ BSs with $n_b$ transmit antennas coordinate their transmissions to $M$ UEs with $n_M$ receive antennas. To combat the inter-cell interference, all BSs transmit following an CoMP-JP strategy based on BD-ZF [27]. Considering the input-output relationship in the CoMP-JP system as:

$$\begin{bmatrix}
    y_1 \\
    y_2 \\
    \vdots \\
    y_M
\end{bmatrix} = \mathbf{H} \mathbf{x} + \mathbf{n} = \begin{bmatrix}
    \mathbf{H}_{11} & \mathbf{H}_{12} & \cdots & \mathbf{H}_{1B} \\
    \mathbf{H}_{21} & \mathbf{H}_{22} & \cdots & \mathbf{H}_{2B} \\
    \vdots & \vdots & \ddots & \vdots \\
    \mathbf{H}_{M1} & \mathbf{H}_{M2} & \cdots & \mathbf{H}_{MB}
\end{bmatrix} \begin{bmatrix}
    \mathbf{x}_1 \\
    \mathbf{x}_2 \\
    \vdots \\
    \mathbf{x}_B
\end{bmatrix} + \begin{bmatrix}
    \mathbf{n}_1 \\
    \mathbf{n}_2 \\
    \vdots \\
    \mathbf{n}_M
\end{bmatrix} \tag{11}
$$

where $y_i$ is the $n_b \times 1$ signal received on the $i$-th UE, $\mathbf{x}_i$ is the $n_b \times 1$ signal transmitted by the $k$-th BS, $\mathbf{n}$ denotes the receiver noise at the $i$-th UE containing $n_M$ circularly symmetric complex Gaussian components with variance $E[\mathbf{n}\mathbf{n}^H] = \sigma^2 \mathbf{I}$, and each $\mathbf{H}_i$ is the $n_M \times n_b$ channel matrix between the $k$-th BS and the $i$-th UE.

The signal transmitted by all $n_b \cdot B$ antennas is:

$$\mathbf{x} = \sum_{i=1}^{M} \mathbf{Q}_i \mathbf{b}_i \in \mathbb{C}^{n_b \cdot B \times 1} \tag{12}$$

where $\mathbf{b}_i$ is the symbol stream with $m_i$ components associated to the $i$-th UE and $\mathbf{Q}_i$ denotes the $B \times n_b$ precoding matrix containing transmit beamforming vectors and power allocation for each symbol stream $\mathbf{b}_i$.

The structure of the precoding matrix $\mathbf{Q}_i$ is such that it avoids interference between UEs’ symbol streams and jointly maximizes UEs’ transmission rates. So, we will define the overall structure of the precoding matrix as:

$$\mathbf{Q}_i = \mathbf{V}_i \mathbf{S}_i \quad i = 1, \ldots, M \tag{13}$$

where $\mathbf{V}_i$ is the BD-ZF precoding matrix and $\mathbf{S}_i$ is the MIMO symbol precoding matrix describing the MIMO precoding and the power allocated per symbol stream $\mathbf{b}_i$. $\mathbf{V}_i$ is such that it avoids interference between UEs symbol streams; its design is based on BD and depends on how coordination between BSs is performed. $\mathbf{S}_i$ is designed to maximize UEs rates and jointly allow Channel Diagonalization; its structure depends on the power restrictions imposed to the maximization problem.

The signal received by the $i$-th UE is affected only by its $n_M \times B \times n_b$ channel matrix $\mathbf{H}_i = [\mathbf{H}_{i1} \mathbf{H}_{i2} \cdots \mathbf{H}_{iB}]$ (the corresponding $n_M$ rows from $\mathbf{H}$ defined in (11)), containing the channel gains between the transmitting antennas at the $B$ BSs and its $n_M$ receiving antennas:

$$y_i = \mathbf{H}_i \mathbf{x}_i + \mathbf{n}_i = \mathbf{H}_i \mathbf{V}_i \mathbf{S}_i \mathbf{b}_i + \mathbf{H}_i \sum_{j=1, j \neq i}^{M} \mathbf{V}_j \mathbf{S}_j \mathbf{b}_j + \mathbf{n}_i \quad i = 1, \ldots, M \tag{14}$$
If we have chosen \( \mathbf{V}_i \) properly to avoid inter-UE symbol streams interference (as described in next section 5.1), the achievable rate for messages directed to the \( i \)-th UE is:

\[
    r_i = \log_2 \left( \mathbf{I} + \mathbf{E} \left[ \mathbf{y}_i \mathbf{y}_i^H \right] \right) = \log_2 \left( \mathbf{I} + \mathbf{N}_i^{-1/2} \mathbf{H} \mathbf{V}_i \mathbf{S}_i \mathbf{S}_i^H \mathbf{H}_i^H \mathbf{N}_i^{-1/2} \right) \quad i = 1, \ldots, M
\]

being \( \mathbf{N}_i \) the correlation matrix of the noise \( \mathbf{n} \) plus interference at the receiver.

The total power transmitted by the \( k \)-th BS is given by:

\[
    P_k = \text{tr} \left( \mathbf{E} \left[ \mathbf{x}_k \mathbf{x}_k^H \right] \right) = \text{tr} \left( \sum_{i=1}^{M} \tilde{\mathbf{Q}}_i \tilde{\mathbf{Q}}_i^H \right) \quad k = 1, \ldots, B
\]

where \( \mathbf{x}_k \) is the \( n_B \times 1 \) signal transmitted by the \( k \)-th BS and \( \tilde{\mathbf{Q}}_i \) contains the \( n_B \) rows of \( \mathbf{Q}_i \) used by the \( k \)-th BS in the transmission of message to the \( i \)-th RS. Alternatively, we can express the per-BS transmit power in terms of the precoding matrices defined in (13) introducing matrix \( \mathbf{B}_k \):

\[
    \mathbf{B}_k = \text{diag} \left( 0, \ldots, 0, 1, \ldots, 1, 0, \ldots, 0 \right) \quad k = 1, \ldots, B
\]

which describes the \( n_B \) rows of \( \mathbf{Q}_i \) used by the \( k \)-th BS to transmit. Then:

\[
    P_k = \text{tr} \left( \sum_{i=1}^{M} \mathbf{B}_k \mathbf{Q}_i \mathbf{Q}_i^H \right) = \text{tr} \left( \sum_{i=1}^{M} \mathbf{B}_k \mathbf{V}_i \mathbf{S}_i \mathbf{S}_i^H \mathbf{V}_i^H \right) \quad k = 1, \ldots, B
\]

Else, assuming per-antenna power constrains, the power transmitted by \( l \)-th antenna of the \( k \)-th BS is:

\[
    P_{ik} = \mathbf{E} \left[ \left| x_{il} \right|^2 \right] = \sum_{i=1}^{M} \tilde{q}_i \tilde{q}_i^T
\]

where \( x_{il} \) is the \( l \)-th component of the signal \( \mathbf{x}_k \) and \( \tilde{q}_i \) is the \( l \)-th row of \( \tilde{\mathbf{Q}}_i \).

### 5.1 Block Diagonalization – Zero Forcing precoding

The key idea of Zero-forcing network coordination is Block Diagonalization. Each antenna weight precoding vector is selected so that each UE symbol stream does not interfere with others UE symbol streams. In other words, each antenna weight precoding vector has to be orthogonal to the subspace spanned by other UE’ channels. Alternatively, a UE’ own symbol stream can interfere with each other.

The structure of the BD-ZF precoding matrix \( \mathbf{V}_i \) depends on how coordination between BSs is performed. The coordination can be done through the cooperation of all the BSs in the coordinated area. But, if one user is so far enough from one BS, it is intuitive to think that this BS is not going to contribute in the transmission to this user. For that reason, we propose to analyze two different transmission strategies:

- **One strategy** in which the BSs coordination is performed between \( B \) BSs and \( M \) UEs (being \( B \) all the BSs in the coordinated area and \( M \) all the UEs in the coordinated area). It will be called **CoMP-JP full coordination** as all the BSs serve simultaneously all the UEs in the macrocell.
- **Another strategy** where the BSs coordination is performed between \( b \) BSs and \( m \) UEs (being \( b < B \), and \( m \) a submultiple of the total number of UEs in the macrocell, \( M \)). This transmission strategy will be denoted **CoMP-JP partial coordination** as \( b < B \).

In CoMP-JP full coordination, each UE receives from all the BSs in the coordinated area. Hence, UEs are not interfered by other UEs transmissions and inter-cell interference is deleted.

In CoMP-JP partial coordination, each UE is served by \( b \) closing BSs and then, if we consider different partial coordination transmissions simultaneously in time, inter UE symbol streams interference is created (as Block Diagonalization is only performed by the coordinated BSs). So,
each user is receiving inter-cell interference from those BSs which do not coordinate the transmissions to it.

The CoMP-JP partial coordination has the benefits that those base stations which do not contribute in the transmission of one specific user, will not need to spend power to force a zero in the direction of that user, and those BSs may use the power to serve other UEs. At the same time, the inter-cell interference has to be evaluated. Therefore, the evaluation of this transmission strategy intend to determine if the received inter-cell interference is lower than the capacity increase due to the allocated power increase.

Next sections 5.1.1 and 5.1.2 details the structure of the BD-ZF precoding matrix $V_i$ for the CoMP-JP full coordination and partial coordination strategies, respectively. In section 5.1.3 we compare the restriction that both strategies impose over the number of UEs and transmission modes for an hexagonal deployment. In section 5.1.4 the simulation results are presented, where the transmission strategies are evaluated and compared to a MU-MIMO transmission with uncoordinated BSs.

### 5.1.1 CoMP-JP Full coordination

We shall consider that each UE is served from $B$ BSs and those $B$ BSs coordinate their transmissions to all $M$ UEs in the system. The BD-ZF precoder design requires that the columns of $V_i$ form a basis set in the null space of other $(M-1)$ UEs channel matrix:

$$V_i \in \text{kernel}(\tilde{H}_i)$$

where

$$\tilde{H}_i = \begin{bmatrix} H^T_1 & H^T_2 & \cdots & H^T_i & H^T_{i+1} & \cdots & H^T_M \end{bmatrix}^T \in \mathbb{C}^{(M-1)\cdot n_B \times B\cdot n_B}$$

The existence of a kernel of appropriate rank requires $\tilde{H}_i$ to be a rectangular matrix with a major number of columns than rows:

$$B\cdot n_B > (M-1)\cdot n_M$$

and hence:

$$\text{rank}(H_i, V_i) \leq \min\left(n_M, (B\cdot n_B - (M-1)\cdot n_M)^+\right)$$

In the same way, the DoF are given by:

$$\text{DoF} = \min\left(n_M, (B\cdot n_B - (M-1)\cdot n_M)^+\right)$$

Additionally, symbol decidability at the receivers requires:

$$\sum_{j=1}^{M} m_j \leq Bn_B$$

$$m_i \leq \text{rank}(H_i, V_i) \quad i = 1, \ldots, M$$

So each symbol stream $b_i$ is precoded with the $B\cdot n_B \times (B\cdot n_B - (M-1)\cdot n_M)$ BD-ZF precoding matrix $V_i$ that satisfies:

$$H_j V_i = 0 \quad \text{for all } j \neq i$$

and hence every UE is not interfered by other UEs transmissions. In other words, Block Diagonalization is performed over the $M\cdot n_B \times B\cdot n_B$ channel matrix $H$ from (11).

This way, the signal received at each UE from (14) can be simplified to:

$$y_i = H_i V_i S_i b_i + n_i \quad i = 1, \ldots, M$$
5.1.2 CoMP-JP Partial coordination

Let us considerer that each UE is served from $b$ adjacent BSs ($b < B$) and, assuming a symmetric scenario, those $b$ BS coordinate their transmissions to $m$ UEs (being $m$ a submultiple of $M$). The total number of UEs in the system is:

$$M = mn_{\text{groups}}$$

(24)

where $n_{\text{groups}}$ refers to the number of disjoint groups of $m$ UEs served by the coordination from $b$ adjacent BSs. Note that each UE belongs to one group. Moreover, for each group of $b$ BS, the two BSs situated on the border collaborate in the transmission to another group of $m$ UE. Then, the number of groups of $m$ UEs satisfies:

$$n_{\text{groups}} = B/(b-1)$$

(25)

The key aspect of CoMP-JP partial coordination is that CoMP-JP is performed between $b$ BSs and $m$ UEs simultaneously in time $n_{\text{groups}}$ groups of transmissions, meanwhile each BS force zeros in the directions of those UEs that will coordinate their transmissions to -although they belong to different groups of $m$ UEs-.

Figure 13 illustrates different combinations of CoMP-JP partial coordination. Note that 2-BSs coordination is always possible (since BSs can always be grouped in pairs), while 3-BSs coordination is only possible when $B$ is even and greater or equal to 4, 4-BSs coordination is possible if $B$ is a multiple of 3 and is greater or equal to 6, etc. These statements are taken following the expression in (25) and taking into account that $n_{\text{groups}}$ has to be a positive integer and greater than 1 (if not we’ll have full coordination).

Let us decompose the BD-ZF precoding matrix $V_i$ into $B$ matrices, which are different from 0 for those $b$ BSs coordinating their transmission to the $i$-th UE:

$$V_i = \begin{bmatrix} V_{i1}^T & V_{i2}^T & \cdots & V_{iB}^T \end{bmatrix}^T$$

Then, we can build an equivalent ZF-BD precoding matrix from those $V_{ii}$ different from 0:

$$\tilde{V}_i = \begin{bmatrix} \tilde{V}_{i1}^T & \tilde{V}_{i2}^T & \cdots & \tilde{V}_{iB}^T \end{bmatrix}^T$$

The equivalent BD-ZF precoding matrix $\tilde{V}_i$ for $i$-th UE needs to:

- Force zeros to ($m$-1) UEs served by the same $b$ adjacent BSs:

  $$H_{s_j} \tilde{V}_{s_i} = 0 \quad \text{for all } j \neq i \text{ and } j \in \{ \text{group of } m \text{ MSs} \}$$

  $$\text{and } s \in \{ \text{BSs serving } b \text{ BSs} \}$$

(26)

- Force zeros to ($\min(2,n_{\text{groups}}-1)$-$m$) UEs served by the two BSs in the border that collaborate in the transmissions to other groups of $m$ UE:

  $$H_{s_l} \tilde{V}_{s_y} = 0 \quad \text{for all } l \in \{ \text{adjacent groups of } m \text{ MSs} \}$$

  $$\text{and } y \in \{ \text{BSs serving other groups} \}$$

(27)
This way, we can build an equivalent matrix $\mathbf{H} \in \mathbb{C}^{(m-1)n_{b} \times \min(2, N_{\text{groups}}-1)m n_{M}}$ with the restrictions in (26) and (27). And the BD-ZF precoding matrix $\mathbf{V}_{i}$ can be obtained as:

$$\mathbf{V}_{i} \in \ker(\mathbf{H}_{i})$$

To have at least one vector in $\mathbf{V}_{i}$, we need $\mathbf{H}_{i}$ to be a rectangular matrix with a major number of columns than rows:

$$bn_{b} > (m-1)n_{M} + \min(2, N_{\text{groups}}-1)mn_{M}$$

and hence:

$$\text{rank}(\mathbf{H}_{i} \mathbf{V}_{i}) \leq \min \left( n_{M}, \left( bn_{b} - (m-1)n_{M} - \min(2, N_{\text{groups}}-1)mn_{M} \right)^{+} \right)$$

Therefore, we can express the DoF as:

$$\text{DoF} = \min \left( n_{M}, \left( bn_{b} - (m-1)n_{M} - \min(2, \frac{B}{b-1}-1)mn_{M} \right)^{+} \right)$$

Moreover, symbol decidability at the received requires:

$$\sum_{i=1}^{M} m_{i} \leq b \cdot n_{b}$$

$$m_{i} \leq \text{rank}(\mathbf{H}_{i} \mathbf{V}_{i}) \quad i = 1, ..., M$$

The existence of the kernel in (28) imposes a harder restriction over the number of transmissions modes $m_{i}$ per user $i$. The following Table 5 summarizes the DoF for a given number of BSs and UEs in the coordinated area.

**Table 5: DoF comparison in CoMP-JP full coordination and partial coordination**

<table>
<thead>
<tr>
<th>$B=3, b=2, M=6$</th>
<th>CoMP-JP full coordination: $\text{DoF}=\min(n_{M}, 3n_{b} \cdot 5n_{M})$</th>
<th>CoMP-JP partial coordination: $\text{DoF}=\min(n_{M}, 2n_{b} \cdot 5n_{M})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B=4, b=2, M=8$</td>
<td>CoMP-JP full coordination: $\text{DoF}=\min(n_{M}, 4n_{b} \cdot 7n_{M})$</td>
<td>CoMP-JP partial coordination: $\text{DoF}=\min(n_{M}, 2n_{b} \cdot 5n_{M})$</td>
</tr>
<tr>
<td>$B=4, b=3, M=8$</td>
<td>CoMP-JP full coordination: $\text{DoF}=\min(n_{M}, 4n_{b} \cdot 7n_{M})$</td>
<td>CoMP-JP partial coordination: $\text{DoF}=\min(n_{M}, 3n_{b} \cdot 7n_{M})$</td>
</tr>
</tbody>
</table>

Since each BS is not forcing zeros in the directions of all $M$ UE (as it is imposed in CoMP-JP full coordination), inter-cell interference is created. Hence, the signal received at each UE (14) has an additional interference -which, in the simulation results, we will suppose omnidirectional for simplicity- from those BS that does not collaborate in the transmission to the $i$-th UE (does not force zeros in its direction):

$$y_{i} = \mathbf{H}_{i} \mathbf{V}_{i} \mathbf{s}_{i} + \mathbf{b}_{i} + \mathbf{n}_{i} + \mathbf{e}_{\text{interp}} \quad i = 1, ..., M$$

**5.1.3 Practical case: hexagonal deployment**

Considering the hexagonal deployment detailed in chapter 4, BSs coordination can be performed between -as maximum- 3 BSs. Then, CoMP-JP full coordination refers to 3-BSs coordination ($B=3$) while CoMP-JP partial coordination refers to 2-BS coordination ($b=2$ and, consequently, $N_{\text{groups}}=3$). See Figure 14.

The maximum number of UEs served simultaneously on each CoMP-JP access mode is limited by the restrictions of the BD-ZF performance detailed in (20) and (28). Developing (20) the restriction for CoMP-JP full coordination can be obtained as:

$$M_{\text{full}} \leq \frac{3n_{b}}{n_{M}}$$

(32)
while in CoMP-JP partial coordination, the restriction (28) when jointly using (24) requires:

\[ M_{\text{partial}} \leq \frac{2n_B}{n_M} \]  

Moreover, as it is imposed by equation (24), \( M_{\text{partial}} \) must be a multiple integer of \( N_{\text{groups}}=3 \).

It can be observed in restrictions (32) and (33), that CoMP-JP partial coordination imposes a harder restriction on the number of UEs that can be served simultaneously on the same time and frequency band. In a particular scenario with 3 BSs with \( n_B=4 \) transmit antennas and \( M \) UEs with \( n_M=1 \) receive antennas, the maximum number of UEs served simultaneously in CoMP-JP full coordination would be \( M=12 \) UEs, while the CoMP-JP partial coordination access mode could support \( M=6 \) UEs \((m=2 \text{ UEs at each group})\). This configuration is illustrated in Figure 14.

So, even thought initially it seemed that CoMP-JP partial coordination access might transmit more streams simultaneously, as fewer restrictions were imposed by the BD-ZF, the number of streams that can be transmitted simultaneously is lower because the coordination is done between fewer transmitting antennas.

In contrast, the great advantage of CoMP-JP partial coordination is that each BSs will only need to allocate power to those users that it will serve: 4 UEs in the described deployment. Meanwhile in CoMP-JP full coordination each BSs has to force zeros -it means to allocate power- to all the UEs in the macrocell (12 UEs in the previous configuration). So, less power can be allocated to each UEs.

![Figure 14: CoMP-JP full coordination (B=3, M=12) and CoMP-JP partial coordination (B=3, M=6, b=2, m=2) schemes in the downlink.](image)

**5.1.4 Simulation results**

The evaluation of the proposed approach is done on a radio access network based on LTE-A specifications [5]. A hexagonal deployment is considered (see section 4.1) and an outdoor homogeneous scenario is deployed (see section 4.2.1), following the simulation parameters detailed in section 4.2.4. \( B=3 \) BSs are deployed. The number of antennas is \( n_B=4 \) at the BS and \( n_M=1 \) at the UE. Inter site distance is 500 m.

In the following study, CoMP-JP full coordination, CoMP-JP partial coordination and non-coordinated BS transmissions are evaluated, to further compare which access mode provides a higher transmission rate in each position of the macrocell arrangement. In the non-coordinated BS transmission strategy, no coordination between the BSs is considered so it turns out to be like a MU-MIMO technique where each BS serves its associated UEs, and then each UE is affected by the inter-cell interference from the 2 non-serving BSs.
The evaluation is done in Topology A (without inter-macrocell interference) and in Topology B (with inter-macrocell interference). Each UE’s position is evaluated with the same conditions for the three access modes (‘CoMP-JP full coordination’, ‘CoMP-JP partial coordination’ and ‘No coordination’ in figures). The results are taken without shadowing effects to avoid random spatial maps.

Figure 15 represents the transmission rate $r_i$ obtained by $i$-th UE on the $i$-th position given by equation (15), for each transmission strategy and topology.

Figure 16 display the probability density function (pdf) of the user’s higher transmission rate in Topology A and B, respectively. The user’s higher transmission rate is given, for each position, by the access mode that provides a higher transmission rate.

![Figure 15: User’s transmission rates obtained on each position in Topology A (left) and Topology B (right), for CoMP-JP full coordination (top), CoMP-JP partial coordination (centre) and no coordination (bottom). ISD is 500m.](image)

When comparing simulation results in Topology A (left) and Topology B (right) in Figure 15, it can be observed that users on the cell-edge are strongly affected by the inter-macrocell
interference (considered in Topology B). Meanwhile users in the centre of the macrocell are also affected by the inter-macrocell interference, but in a milder way.

When no inter-macrocell interference is considered (Topology A) the best strategy for all the positions in the macrocell arrangement is CoMP-JP full coordination, as it can be observed in Figure 15 and Figure 16. It is due to the distance between the BSs (ISD=500m): BSs are close enough to obtain large benefits from the BSs cooperation, as it allows to delete the inter-cell interference. In CoMP-JP partial coordination and non-coordinated access modes, the users far-from the BSs are strongly affected by the inter-cell interference (interference from those BSs that do not cooperate in their transmission). This behaviour is more remarkable in the non-coordinated strategy, as 2 BSs are generating inter-cell interference.

When inter-macrocell interference is considered (Topology B), in the centre of the macrocell the best strategy is CoMP-JP full coordination. Even so, at those points between two BSs, is better to use CoMP-JP partial coordination, although the rates achieved are not too high as the transmission rate obtained in the centre of the macrocell (see probability density function in Figure 16).

To conclude, it can be observed that, in general, the best transmission strategy is CoMP-JP full coordination when ISD=500m, as it is able to delete the inter-cell interference due to the coordination and cooperation of the BSs.

![Figure 16: Probability density function (pdf) of the higher user’s transmission rates, and access mode that allows it, in Topology A (left) and Topology B (right). ISD is 500m.](image)

### 5.2 Rate maximization precoding

Once established the interference-nulling BD-ZF precoding, and we have seen the restrictions it imposes on the number of users and transmit and receive antennas, we need to find the optimal structure of the MIMO symbol precoding matrix $S_i$ to complete the whole precoding matrix $Q_i = V_i S_i$.

The matrix $S_i$ is designed to maximize UEs rates. So, its optimal structure depends on how many power restrictions we impose to the maximization problem: a single power constraint (referred to the sum power) or per-BS power constraints.

Moreover, $S_i$ is such that it allows Channel Diagonalization at the receiver. Channel Diagonalization is satisfied if the precoding matrix, when jointly deployed with a unitary decoding matrix at the receiver, is able to diagonalize the MIMO channel into parallel scalar sub-channels, over which independent encoding and decoding can be applied to simplify the transceiver design.
5.2.1 Sum power constraint

When we have a single constraint over the whole power transmitted by all $B$ BSs, the optimal structure for $S_i$ is such that it maximizes UEs’ rate $r_i$ from (15):

$$r_i = \log_2 \left| I + N_i^{-1/2} H_i V_i S_i S_i^H V_i^H H_i^H N_i^{-1/2} \right|$$

(34)

As we want to maximize the transmission rates $r_i$ of all the users ($i=1,...,M$), the maximization problem consist on maximizing an objective function that relates all of them. We will use the weighted sum rate (WSR) which allows adding certain Quality of Service (QoS) over the served users depending on priorities $\mu_i$. Otherwise we can use the sum rate (SR), in which case $\mu_i = 1$.

Hence, we are ready to present the weighted sum-rate maximization problem for the downlink transmission in CoMP-JP with BD-ZF precoding and sum power constraint as follows:

$$\text{maximize} \quad \sum_{i=1}^{M} \mu_i \log_2 \left| I + N_i^{-1/2} H_i V_i T_i T_i^H V_i^H H_i^H N_i^{-1/2} \right|$$

subject to

$$\sum_{i=1}^{M} \text{tr}(T_i) - BP_{\text{max}} \leq 0$$

(35)

where $P_{\text{max}}$ denotes the per-BS available power. We have considered $T_i = S_i S_i^H$ as design variables instead of the precoding matrices $S_i$, so the optimization is done over the set of positive definite matrices $T_{ij},...,T_{it}$. The sum power constraint is simplified from (17) due to the fact that tr($AB$)=tr($BA$) and taking into account that $V_i$ is the BD-ZF precoding matrix (so it satisfies: $V_i^H V_i = I$). In addition to the single power constraint, the second constraints impose $T_i$ to be positive definite matrices and Hermitian.

If we considerer $T_i = S_i S_i^H$ it is easy to verify that (35) turns out to be a convex optimization problem, since the objective function is concave over $T_i$’s and all the constraints specify a convex set over $T_i$’s. Then, (35) can be solved using standard convex optimization techniques, e.g., interior-point method [32]. However, let us considerer the following (reduced) SVD:

$$N_i^{-1/2} H_i V_i = U_i \Lambda_i W_i^H$$

(36)

Then, the optimal structure for $T_i$ to maximize the problem in (35) is given by the following structure [14]:

$$T_i^* = W_i P_i W_i^H \quad i = 1,...,M$$

(37)

where $W_i$ is a unitary matrix containing the $m_i$ right singular vectors of $N_i^{-1/2} H_i V_i$, associated to the largest singular vectors, and $P_i$ is a $m_i \times m_i$ diagonal matrix containing the power allocated to each symbol stream $P_i = \text{diag}(p_{i1}, ..., p_{im_i})$, whose optimal values are obtained by the standard water-filling algorithm as:

$$p_{ij} = \left( K \mu_i - \frac{1}{\lambda_{ij}} \right)^+ \quad i = 1,...,M \quad j = 1,...,m_i$$

(38)

where $\lambda_{ij}$ are the eigenvalues of $N_i^{-1/2} H_i V_i$ in (36); $\Lambda_i = \text{diag}(\lambda_{i1}, ..., \lambda_{im_i})$ and $K$ is such that satisfies with equality the sum power constraint:

$$\sum_{i=1}^{M} \text{tr}(W_i P_i W_i^H) = \sum_{i=1}^{M} \sum_{j=1}^{m_i} p_{ij} = BP_{\text{max}}$$

Proof: The proof of the optimal structure for $T_i$ in (37) with the power allocation in (38) is developed in Annex B.
Finally, we have to undo the variable change $T_i = S_i S_i^H$. Since $P_i$ is a diagonal matrix, we can easily obtain the optimal MIMO symbol precoding matrix $S_i^*$ to maximize the weighted sum-rate subject to the sum power constraint as:

$$S_i^* = W_i^{1/2} P_i^{1/2}, \quad i = 1, \ldots, M$$ (39)

Once established the optimal structure for the MIMO precoding matrix, the achievable rate for messages directed to the $i$-th UE from (34) can be developed:

$$r_i = \log_2 \left| I + N_i^{-1/2} H_i V_i S_i^* V_i^H H_i^H N_i^{-H/2} \right| = \log_2 \left| I + U_i \Lambda_i P_i \Lambda_i^H U_i^H \right|$$

$$= \log_2 \left| I + \Lambda_i P_i \Lambda_i^H \right| = \sum_{j=1}^m \log_2 \left( 1 + \lambda_j^2 p_i \right)$$ (40)

Moreover, we can verify that the optimal MIMO symbol precoding matrix $S_i^*$ satisfies the “Channel Diagonalization” property. The received signal for the $i$-th UE is:

$$y_i = H_i V_i S_i^* b_i + n_i = H_i V_i W_i^{1/2} b_i + n_i$$

Then, each UE may independently rotate the received signal and decouple the different symbol streams, as the MIMO channel is diagonalized into parallel scalar sub-channels:

$$\tilde{y}_i = U_i^{1/2} y_i = U_i^{1/2} U_i \Lambda_i W_i^{1/2} P_i^{1/2} b_i + \tilde{n}_i = \Lambda_i P_i^{1/2} b_i + \tilde{n}_i = \left[ \begin{array}{c} \lambda_{i1} p_i^{1/2} b_{i1} \\ \vdots \\ \lambda_{im} p_i^{1/2} b_{im} \end{array} \right] + \tilde{n}_i$$ (41)

where the noise vector $\tilde{n}_i = U_i^H N_i^{-1/2} n_i$ turns out white owing to the $N_i^{-1/2}$ transformation, and remains white with covariance $\sigma_i^2 I$ due to the to the unitary transformation ($U_i^H$).

### 5.2.2 Per-BS power constraint

When we have per-BS power constraints, the optimal solution for the MIMO symbol precoding matrix $S_i$ does not follow the structure detailed in (39). In the following section 5.2.2.1 the optimal solution is presented. In section 5.2.2.2 two suboptimal and low complexity solutions are proposed.

#### 5.2.2.1 Optimal solution

If we consider $T_i = S_i S_i^H$, when maximizing UEs’ rate $r_i$ from (15) subject to per-BS power constraints, the weighted sum-rate maximization problem for the downlink transmission in CoMP-JP with BD-ZF precoding and per-BS power constraints turns out to be:

$$\max_{T_i} \sum_{i=1}^M \mu_i \log_2 \left| I + N_i^{-1/2} H_i V_i T_i V_i^H H_i^H N_i^{-H/2} \right|$$

s.t.

$$\begin{align*}
\text{tr} \left( \sum_{i=1}^M B_k V_i T_i V_i^H \right) - P_{\text{max}} & \leq 0, \quad k = 1, \ldots, B \\
T_i & \succeq 0, \quad T_i = T_i^H, \quad i = 1, \ldots, M
\end{align*}$$ (42)

where $P_{\text{max}}$ denotes the per-BS available power, $B_k$ is defined in (16) and $\mu_i$ is the priority given for the $i$-th UE in order to add some QoS over the served users. We have used $T_i$’s instead of the MIMO symbol precoding matrices $S_i$’s as design variables and the optimization is done over those variables. In addition to the per-BS power constraints, $T_i$ needs to be positive definite matrices and Hermitian, which is imposed by the second constraints in (42).

It is easy to verify that (42) is a convex optimization problem, as it verifies all the properties: the objective function is concave over $\{T_i\}$ and all the constraints specify a convex set over $\{T_i\}$. 
Therefore, it can be solved using standard convex optimization techniques. However, the optimal structure for $T_i$ can also be found using Lagrange duality methods.

Denote $\{\gamma_k\}$ a set of non-negative dual variables associated to the $k$-th per-BS power constraint, the optimal solution to (42) for fixed $\{\gamma_k\}$ is given by [35]:

$$T^*_i = \left( V_i^H B_i V_i \right)^{1/2} \hat{W}_i \hat{W}_i^H \left( V_i^H B_i V_i \right)^{1/2} (43)$$

where $B_i = \sum_{k=1}^{B} \gamma_k B_k = \text{diag} \left( \left[ \gamma_1 \gamma_2 \ldots \gamma_B \right] \right) \otimes I_{a_i}$, $B_k$ is defined in (16) and $\otimes$ denotes the Kronecker product, while $\hat{W}_i$ is obtained from the following (reduced) SVD:

$$N_i^{1/2} H_i \left( V_i^H B_i V_i \right)^{1/2} = \hat{U}_i \hat{\Lambda}_i \hat{W}_i^H (44)$$

where $\hat{A}_i = \text{diag}(\hat{\lambda}_1, \ldots, \hat{\lambda}_M)$ is a diagonal matrix, and $\hat{P}_i = \text{diag}(\hat{\rho}_1, \ldots, \hat{\rho}_m)$ is obtained from the standard water-filling algorithm:

$$\hat{\rho}_j = \left( \frac{\mu}{\ln(2)} - \frac{1}{\hat{\lambda}_j} \right)^+ (45)$$

**Proof:** The proof of the optimal structure for $T_i$ in (43) is developed in Annex C.

When the optimal solution for $\{\gamma_k\}$ is obtained, the corresponding solution in (43) becomes optimal for (42). Then we need to initialize $\{\gamma_k\}$ properly and update the Lagrange multipliers $\gamma_k$ $k = 1, \ldots, B$ accordingly to the following subgradient:

$$d_k = \text{tr} \left( \sum_{i=1}^{M} B_i V_i T_i \right) - P_{\max} (46)$$

The subgradient is computed in order to update the set of variables $\{\gamma_k\}$ properly. The correct procedure is: once calculated the optimal values for $T^*_i$ from (43) for a fixed set $\{\gamma_k\}$, we should compute the subgradient $d_k$ with the obtained $T^*_i$, and it will indicates us how to update the set of $\{\gamma_k\}$ for the next iteration. If the subgradient $d_k$ is positive, it indicates that the $k$-th BS is using more power than the allowed $P_{\max}$, so we have to increase or decrease the value of $\gamma_k$ in order not to exceed the allowed power. As $T^*_i$ depends on all the set $\{\gamma_k\}$ we cannot decide how to actualize each $\gamma_k$, but we can update all of them simultaneously by using, for example, the Ellipsoid method [34]. The algorithm to solve (42) is detailed in Table 6.

After all, we have to undo the variable change $T_i = S_i S_i^H$. Hence, the optimal MIMO symbol precoding matrix $S_i^*$ to maximize the weighted sum-rate subject to per-BS power constraints is given by:

$$S_i^* = \left( V_i^H B_i V_i \right)^{1/2} \hat{W}_i \hat{W}_i^H (47)$$

Note that $S_i^*$ consists of non-orthogonal columns if $B_i^*$ is a non-identity diagonal matrix (i.e., the optimal $\{\gamma_k\}$ are not all equal). Moreover, it can be verified that for the sum-power constraint case $S_i^*$ consists of orthogonal columns (beamforming vectors) since $V_i^H V_i = I$ and its structure is independent of $\gamma$ and becomes the result obtained in section 5.2.1.

**Table 6: Algorithm solving $S_i$ when per-BS power constraint**

1. Initialize: $\gamma_k$ $k = 1, \ldots, B$
2. Repeat:
   - Solve $T_i$ $i = 1, \ldots, M$ using (43) for the given $\gamma_i$'s
   - Compute the subgradient in (46) and update $\gamma_i$'s accordingly based on the ellipsoid method [28]
3. Until all $\gamma_i$'s converge
4. Compute optimal $S_i^*$ given by (47)
Solving the case with per-BS power constraints increases the computational complexity since we have to compute one SVD per iteration (the SVD is implicit in the computation of $T$). For that reason, it is very important to initialize $\{\lambda_k\}$ properly.

Once established the optimal structure for the MIMO symbol precoding matrix $S^*_i$, when per-BS power constraints are imposed, we can develop the achievable rate (15) for messages directed to the $i$-th UE:

$$r_i = \log_2 \left| I + N_i^{-1/2} H_i V_i S_i^* V_i^H N_i^{-H/2} \right| = \log_2 \left| I + \hat{U}_i \hat{\Lambda}_i \hat{P}_i \hat{V}_i^H \hat{U}_i^H \right|$$

$$= \log_2 \left| I + \hat{\Lambda}_i \hat{P}_i \hat{V}_i^H \right| = \sum_{j=1}^{m} \log_2 \left( 1 + \hat{\gamma}_j^2 p_{y_j} \right) \quad (48)$$

Finally, we can verify that the optimal MIMO symbol precoding matrix $S^*_i$ satisfies the “Channel Diagonalization” property as it is able to diagonalize the MIMO channel into parallel scalar sub-channels. The received signal for the $i$-th UE is:

$$y_i = H_i V_i S_i^* b_i + n_i = H_i V_i \left( V_i^H b_i \right)^{1/2} \hat{W}_i^{1/2} b_i + n_i$$

and each UE may independently rotate the received signal and decouple the different symbol streams with the following transformation:

$$\tilde{y}_i = \hat{U}_i^H N_i^{-1/2} y_i = \hat{U}_i^H \hat{U}_i \hat{\Lambda}_i \hat{W}_i^{1/2} b_i + \hat{n}_i = \hat{\Lambda}_i \hat{P}_i^{1/2} b_i + \hat{n}_i = \begin{bmatrix} \hat{\gamma}_{11} p_{11}^{1/2} b_{11} \\ \vdots \\ \hat{\gamma}_{m1} p_{m1}^{1/2} b_{m1} \end{bmatrix} + \hat{n}_i \quad (49)$$

where the noise vector $\hat{n}_i = \hat{U}_i^H N_i^{-1/2} n_i$ remains white with covariance $\sigma^2 I$ owing to the unitary transformation.

5.2.2.2 Low-complexity solutions

In previous section 5.2.2.1, it was observed that the closed-form solution for $S_i$ when per-BS power constraints are imposed can be found applying convex optimization techniques, but we need an iterative algorithm to finally converge. It makes the problem computationally complex. For that reason, in this section we propose and evaluate two low complexity and simplest solutions for the power allocation when per-BS power constraints are imposed in order to reduce the computational complexity of the algorithm detailed in Table 6.

1. Scaled-sum power constraint solution

The first solution consist on assume the structure for the MIMO symbol precoding matrix $S_i$ when sum power constraint is imposed (developed in section 5.2.1): $S_i = WP^{1/2}$, and after scale the power assigned to each transmission mode of each $i$-th UE in order to satisfy all the per-BS power constraints: $P \to \kappa P$.

The scaling factor ($\kappa < 1$) will be determined by the BSs which consume more power, the more restrictive BSs:

$$\kappa = P_{\max} \left( \max_{k=1, \ldots, K} \text{tr} \sum_{i=1}^{M} B_k V_i S_i^* V_i^H \right)^{-1} \quad (50)$$

Then, the achievable rate for messages intended to the $i$-th UEs result:

$$r_i = \sum_{j=1}^{m} \log_2 \left( 1 + \kappa \hat{\gamma}_j^2 p_{y_j} \right) \quad (51)$$
2. SVD-based solution

Otherwise we can assume the structure for the MIMO symbol precoding matrix detailed in (39) for the sum power constraint case: $S_i = WP_i^{\mu/2}$; maintaining the SVD structure for the matrix $W$, defined in (36) and apply convex optimization methods to find the optimal $P_i$ when per-BS power constraints are imposed to the maximization problem:

$$\text{maximize} \quad \sum_{i=1}^{M} \mu_i \log_2 \left| I + N_i^{-1/2} H_i V_i W_i P_i W_i^H V_i^H N_i^{-1/2} \right|$$

$$\text{s.t.} \quad \left\{ \begin{array}{l}
\text{Tr} \left( \sum_{i=1}^{M} B_i V_i W_i P_i W_i^H V_i^H \right) - P_{\text{max}} \leq 0 \quad k = 1, \ldots, B \\
P_i \geq 0 \quad i = 1, \ldots, M
\end{array} \right. \quad (52)$$

It can be observed that (52) is a convex problem over $P_i$, so we can apply convex optimization techniques to solve it and find the optimal power allocation values.

Compared to the optimal solution for the MIMO symbol precoding matrix $S_i$ when per-BS power constraints are imposed (47), in both suboptimal and lower complexity solutions we only have to compute one SVD, which strongly reduces the computational complexity.

5.2.3 Simulation results

The evaluation of the proposed approach is done on a radio access network based on LTE-A specifications [5]. A hexagonal deployment is considered (see section 4.1) and an outdoor homogeneous scenario is deployed (see section 4.2.1), following the simulation parameters detailed in section 4.2.4. $B=3$ BSs are deployed and, on each scenario, $M=6$ users are dropped uniformly in the macrocell arrangement. The number of antennas is $n_t=4$ at the BS and $n_r=1$ at the UE. We consider a MAC overhead of 40% for the BS cooperation and 20% for the MU-MIMO without BS cooperation. Inter site distances are 500, 1000, 1500 and 2000 m.

In the following study, CoMP-JP full coordination is evaluated when per-BS power constraint are imposed. The optimal solution detailed in (47) (‘OPTIM’ in legend) is compared to the two suboptimal solutions proposed in section 5.2.2.2 (‘SVD-based’ and ‘Scaled-sum-PC’ in legend). They are evaluated for the sum rate (SR) and the weighted sum rate (WSR), over 1000 random users. When adopting the WSR as the object function, the weights are inversely proportional to the highest singular value in order to avoid unfair services to deprived users (i.e. $\mu_i = 1/\max \left( \lambda_i \right)$). All these approaches are compared to a MU-MIMO technique without coordination of the BSs under SR criterion (‘No coordination SR’ in legend).

Figure 17 displays cell-edge spectral efficiency vs. cellular spectral efficiency (see computation details in Annex D) in Topology A (without inter-macrocell interference). Figure 18 displays cell-edge spectral efficiency vs. cellular spectral efficiency in Topology B (with inter-macrocell interference). It is important to remark that these results do not assume any modulation constraint. In section 5.4, we will define and evaluate the problem with the modulation constraints.

Significant gains are obtained, both in spectral efficiency and cell-edge spectral efficiency, in the CoMP-JP strategies over the non-coordinated BS transmissions, due to the cooperation of the BSs. The gains are also remarkable as the ISD increases, although the inter-cell interference in the non-coordinated transmission is reduced due to the path-loss effects. In the non-coordinated transmissions, the cell-edge spectral efficiency is 0 even when we do not consider the inter-macrocell interference, as only one BS is serving each user and then the system can be affected by the rank of individual channels. It remarks one of the benefits of CoMP-JP.

Significant losses can be observed when taking into account the inter-macrocell interference produced by the extern macrocells (Topology B), over the case where no inter-macrocell interference is considered (Topology A). This inter-macrocell interference strongly affects the users on the cell-edge, as they are more affected by the interference from the non-serving sectors of the closest BSs (see Figure 15).
When optimizing the WSR, there are some losses in spectral efficiency; but the results are enhanced in terms of cell-edge spectral efficiency, as it is more concerned about users having bad quality channel. This performance is remarked in Topology B, as the inter-macrocell interference strongly affects the worst users. In the other side, when maximizing the SR, the worst users are not a priority, and for that reason the cell-edge spectral efficiency is more close to zero.

The suboptimal and low-complexity solution ‘SVD-based’ achieve similar results in spectral efficiency and cell-edge spectral efficiency to the optimal solution in both topologies. Moreover, its algorithm is faster than the algorithm to find the optimal solution, as we have to compute only one SVD per iteration. So, it is a good and fast approximation to the optimal solution.

Figure 17: Cell-edge spectral efficiency vs. cellular spectral efficiency in CoMP-JP full coordination when per-BS power constraint, with Topology A. ISD are 500m(black), 1000m(blue), 1500m(red) and 2000m(green).

Figure 18: Cell-edge spectral efficiency vs. cellular spectral efficiency in CoMP-JP full coordination when per-BS power constraint, with Topology B. ISD are 500m(black), 1000m(blue), 1500m(red) and 2000m(green).
5.3 CoMP-JP in multicarrier transmissions

Let us consider a frequency-selective MIMO channel, between $B$ BSs with $n_B$ transmit antennas and $M$ UEs with $n_M$ receive antennas, where we use a block transmission strategy. Denoted $N$ the length of each transmitted block (i.e. the number of subcarrier frequencies) and $L$ the (maximum) channel order, the input-output relationship is defined as:

$$
\begin{align*}
\begin{pmatrix}
y_{11} \\
y_{1n} \\
y_{21} \\
y_{2n} \\
y_{31} \\
y_{Mn}
\end{pmatrix} = \mathbf{H} \mathbf{x} + \mathbf{n}
\end{align*}
$$

where $y_{ij}$ is the $N \times 1$ signal received on the $j$-th receive antenna of the $i$-th UEs, $\mathbf{x}$ is the $N \times 1$ signal transmitted on the $l$-th transmit antenna of the $k$-th BSs, $\mathbf{n}$ denotes the receiver noise at the $j$-th receive antenna of the $i$-th UE containing $N$ circularly symmetric complex Gaussian components with variance $E[\mathbf{n,n}^H] = \sigma^2 \mathbf{I}$, and each $H_{ij}$ is a $N \times N$ Toeplitz matrix.

Incorporating a cyclic prefix (CP) of sufficient length, the matrix $H_{ij}$ can be made also circulant. In such a case, each matrix $H_{ij}$ can be diagonalized as:

$$
H_{ij} = \mathbf{W} \Lambda_i \mathbf{W}^H
$$

where $\mathbf{W}$ is the normalized DFT matrix (i.e., $W_{pq} = e^{j2\pi pq/N} / \sqrt{N}$). Then, the overall matrix $\mathbf{H}$ can then be diagonalized as follows:

$$
\mathbf{H} = (\mathbf{I} \otimes \mathbf{W}) \Lambda (\mathbf{I} \otimes \mathbf{W})^H
$$

where $\otimes$ indicates the Kronecker product and

$$
\Lambda = 
\begin{pmatrix}
\Lambda_{11} & \cdots & \Lambda_{1n} & \Lambda_{11} & \cdots & \Lambda_{1n} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\Lambda_{n1} & \cdots & \Lambda_{nn} & \Lambda_{n1} & \cdots & \Lambda_{nn} \\
\Lambda_{11} & \cdots & \Lambda_{1n} & \Lambda_{11} & \cdots & \Lambda_{1n} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\Lambda_{n1} & \cdots & \Lambda_{nn} & \Lambda_{n1} & \cdots & \Lambda_{nn}
\end{pmatrix}
$$

It is easy to verify that $(\mathbf{I} \otimes \mathbf{W})$ is itself a unitary matrix. The capacity of an ergodic frequency-selective channel is then:

$$
r_i = \frac{1}{N} \log_2 \left| 1 + E[\mathbf{y}_i \mathbf{y}_i^H] \right| = \frac{1}{N} \log_2 \left| 1 + \frac{1}{\sigma^2} \Lambda_i E[\mathbf{y} \mathbf{y}^H] \right| \Lambda_i^H
$$

i = 1,...,M

where $\mathbf{y}_i$ is the $Nn_M \times 1$ signal received on the $i$-th UEs: $\mathbf{y}_i = \begin{bmatrix} y_{1i}^H & \cdots & y_{n_Mi}^H \end{bmatrix}^H$ (from $\mathbf{y}$ defined in (53)), and $\Lambda_i$ is the $Nn_M \times Bn_M$ matrix with the $Nn_M$ rows of $\Lambda$ corresponding to the $i$-th UEs:

$$
\Lambda_i = 
\begin{pmatrix}
\Lambda_{i1} & \cdots & \Lambda_{in} & \Lambda_{i1} & \cdots & \Lambda_{in} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\Lambda_{ni} & \cdots & \Lambda_{nn} & \Lambda_{ni} & \cdots & \Lambda_{nn} \\
\Lambda_{i1} & \cdots & \Lambda_{in} & \Lambda_{i1} & \cdots & \Lambda_{in} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\Lambda_{ni} & \cdots & \Lambda_{nn} & \Lambda_{ni} & \cdots & \Lambda_{nn}
\end{pmatrix}
$$

5.3 CoMP-JP in multicarrier transmissions

Access modes based on CoMP for relay transmissions in 4G systems
The normalization by $N$ has been introduced in (56) to measure the capacity in terms of number of bits per transmitted symbol.

Each matrix in (57) is diagonal, so that $\mathbf{A}_i$ is a block matrix with diagonal blocks. Using permutations of rows and columns of $\mathbf{A}_i$ in (57), we can reduce $\mathbf{A}_i$ to a diagonal matrix as:

$$
\mathbf{A}_i' = P_i \mathbf{A}_i P_R = \begin{pmatrix}
\mathbf{A}_i(1) & 0 & \cdots & 0 \\
0 & \mathbf{A}_i(2) & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & \mathbf{A}_i(N)
\end{pmatrix}
$$

(58)

with

$$
\mathbf{A}_i(n) = \begin{pmatrix}
\mathbf{H}_{1i}^1(n) & \cdots & \mathbf{H}_{1i}^{n_i-1}(n) & \mathbf{H}_{2i}^1(n) & \cdots & \mathbf{H}_{2i}^{n_i-1}(n) \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\mathbf{H}_{1i}^{n_i-1}(n) & \cdots & \mathbf{H}_{1i}^{n_i-1}(n) & \mathbf{H}_{2i}^{n_i-1}(n) & \cdots & \mathbf{H}_{2i}^{n_i-1}(n)
\end{pmatrix}
$$

(59)

where $\mathbf{H}_{hi}^j(n) = \sum_{m=1}^{L} h_{hi}^j(m)e^{-j2\pi mn/N}$ is the transfer function of the channel between the $l$-th transmit antenna of the $k$-th BS and the $j$-th receive antenna of the $i$-th UE, evaluated on the $n$-th subcarrier.

Introducing (59) in (56) we obtain:

$$
r_i = \frac{1}{N} \log_2 \left| 1 + \frac{1}{\sigma^2} \mathbf{A}_i^H \mathbf{E}\{\mathbf{x}\mathbf{x}^H\} \mathbf{A}_i \right| = \frac{1}{N} \log_2 \left| 1 + \frac{1}{\sigma^2} \mathbf{A}_i(n) \mathbf{R}(n) \mathbf{A}_i^H(n) \right|
$$

(60)

where $\mathbf{R}(n) = \mathbf{E}\{\mathbf{x}\mathbf{x}^H\}$ is the transmit covariance in the $n$-th subcarrier, being $\mathbf{x}$ the $Bn_B \times 1$ signal transmitted in the $n$-th subcarrier.

Hence, we can decompose the frequency-selective MIMO channel into $N$ flat sub-channels, and the capacity of the frequency-selective MIMO channel is the sum of the $N$ terms and division by $N$ of the capacity of each flat MIMO channel:

$$
r_i = \frac{1}{N} \sum_{n=1}^{N} r(n) \quad i = 1, \ldots, M
$$

(61)

where $r(n)$ is the capacity of the flat MIMO channel in the $n$-th subcarrier.

By this way, we can introduce the precoding matrixes defined in (13) (and after detailed in 5.1 and 5.2) for each subcarrier to further compute the transmission rate in (60) and the power transmitted by each BS. Following the definitions in sections 5.1.1 and 5.2.2, we can find the optimal precoding structure for the transmitted signal on the $n$-th subcarrier by all $Bn_B$ antennas as:

$$
\mathbf{x}_n = \sum_{i=1}^{K} \mathbf{V}_n^{i} \mathbf{W}_n^{i} \mathbf{P}_j^{i} \mathbf{b}_n^{i} \in \mathbb{C}^{n_B \times 1} \quad n = 1, \ldots, N
$$

(62)

where $\mathbf{b}_n^{i}$ is the symbol stream with $m_n^{i}$ components associated to the $n$-th subcarrier of the $i$-th UE. We adopt a conventional BD-ZF precoding defined by three matrices: $\mathbf{P}_j^{i}$ is a diagonal matrix describing the power allocated per symbol stream $\mathbf{b}_n^{i}$, $\mathbf{V}_n^{i}$ is the $Bn_B \times (Bn_B - (R-1)n_B)$ BD-ZF precoding matrix (detailed in section 5.1.1) and $\mathbf{W}_n^{i}$ is the symbol precoding matrix (detailed in section 5.2.2).
5.4 From Shannon capacity bounds to practical LTE-A implementations

The Shannon Capacity bound cannot be reached in practice due to several implementation issues. Then an adjusted Shannon capacity formula needs to be considered in order to achieve an accurate benchmarking of LTE-A.

Recall the SISO Shannon capacity expression for the theoretical channel spectral efficiency in AWGN channel:

\[ S_{\text{shannon}}(\text{bits/s/Hz}) = \log_2(1 + \text{SNR}) \]  

(63)

To represent the losses mechanism, the following modified Shannon capacity expression is used [36]:

\[ S_{\text{modified}}(\text{bits/s/Hz}) = \eta_{\text{BW}} \log_2(1 + \text{SNR}) \]  

(64)

where \( \eta_{\text{BW}} \) accounts for the system bandwidth efficiency of LTE-A. We detail those efficiencies in section 5.4.1.

Furthermore, the capacity expression in (64) has to be upper limited accordingly to the modulations used in the LTE-A [29]. So, the practical capacity expression is affected by the modulation constraints in the following way:

\[ S(\text{bits/s/Hz}) = \min(\eta_{\text{BW}} \log_2(1 + \text{SNR}), S_{\text{max}}) \]  

(65)

where \( S_{\text{max}} \) is the maximum spectral efficiency that can be achieved with the Modulation and Coding Schemes (MCSs) of the LTE-A. Details are given in section 5.4.2.

5.4.1 Bandwidth efficiency

The LTE-A bandwidth efficiency [29] is decreased by several issues listed in Table 7. Due to requirements to Adjacent Channel Leakage Ratio (ACLR) and practical filter implementation, the BW occupancy is reduced to 0.9. The overhead of the Cyclic Prefix (CP) is approximately 7% and the overhead of pilot assisted channel estimation (PO) depends on the number of transmit antennas: approximately 5% for single antenna transmission and 14% for four transmit antennas.

The total results for the LTE-A link-level bandwidth efficiency are given by:

\[ \eta_{\text{BW,link--level}} = \eta_{\text{ACLR}} \times \eta_{\text{CP}} \times \eta_{\text{PO}} \]  

(66)

Further, at the system level, we have additional overhead related to common control channels, such as synchronization channels and broadcast channels. However, the more essential control signalling overhead in LTE-A is related to the downlink shared control channel (normally referred as the Layer 1 and Layer 2 control signalling). This overhead depends on the number of users to be simultaneously scheduled in a cell, the MIMO/beamforming schemes selected and the resource assignment. The overhead in Table 7 corresponds to the scenario: 1 OFDM symbols within each 1ms subframe [29].

Then, the LTE-A system-level bandwidth efficiency can be computed as:

\[ \eta_{\text{BW,system--level}} = \eta_{\text{BW,link--level}} \times \eta_{\text{CC}} \]  

(67)

where \( \eta_{\text{BW,link--level}} \) refers to the link-level bandwidth efficiency and \( \eta_{\text{CC}} \) to the bandwidth efficiency due to the dedicated and control channels.

Note that it is outmost important to consider system bandwidth efficiency when using Shannon capacity to estimate the system performance of LTE-A, otherwise the estimated results will differ from reality.
5.4.2 Modulation constraint

LTE-A downlink systems use several MCSs that can be characterized by a modulation type and a code rate (see Table 8). The maximum spectral efficiency of a given MCS is the product of the code rate \((n/k)\) and the number of bits per modulation symbol \(\log_2(M)\):

\[
S_{\text{max}} \text{ (bits} / \text{s} / \text{Hz}) = \frac{n}{k} \log_2(M)
\]  

(68)

In other words, the highest modulation and coding scheme in 4G systems is limited to about 4.8bits/s/Hz (with 64-QAM and code rate 4/5). MIMO designs allow high user’s bit rates.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Code rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK ((M=4))</td>
<td>1/8, 1/6, 1/5, 1/4, 1/3, 1/2, 2/3, 4/5</td>
</tr>
<tr>
<td>16-QAM ((M=16))</td>
<td>1/2, 2/3, 3/4, 4/5</td>
</tr>
<tr>
<td>64-QAM ((M=64))</td>
<td>1/2, 2/3, 3/4, 4/5</td>
</tr>
</tbody>
</table>

Therefore, in addition to the losses due to the system bandwidth efficiency, the truncated form of the modified Shannon capacity expression (65) is needed in order to approximate the modulation performance.

The LTE-A spectral efficiency considered in this work - for the SISO case - is:

\[
S(\text{bits} / \text{s} / \text{Hz}) = \min \left( \eta_{BW} \log_2 (1 + \text{SNR}), \frac{n}{k} \log_2(M) \right)
\]  

(69)

where \(\eta_{BW}\) refers to the BW efficiency, which depends on the number of transmit antennas as defined in Table 7, and \(n/k\) and \(M\) refer to the MCS which provides a higher spectral efficiency.

Considering the MCSs in Table 8, the spectral efficiency should be truncated to 4.8bits/s/Hz. When considering more complex receivers (i.e. capable of decoding a higher modulation scheme), we could reach higher spectral efficiencies (e.g. 6.4bits/s/Hz with 256QAM 4/5).

See Annex E for further details.

When considering MIMO configurations and/or multicarrier transmissions, the attenuated and truncated form of the Shannon capacity bound defined in (69) has to be applied for each transmission mode of each multicarrier frequency. So, thanks to the use of the MIMO technique and OFDM modulation (see details in section 2.3) we can obtain higher system spectral efficiencies.

5.4.3 Simulation results

The evaluation of the proposed approach is done on a radio access network based on LTE-A specifications [5]. A hexagonal deployment is considered (see section 4.1) and an outdoor
homogeneous scenario is deployed (see section 4.2.1), following the simulation parameters detailed in section 4.2.4. \( B=3 \) BSs are deployed and, on each scenario, \( M=6 \) users are dropped uniformly in the macrocell arrangement. The number of antennas is \( n_T=4 \) at the BS and \( n_R=1 \) at the UE. Inter site distances are 500, 1000, 1500 and 2000 m.

In the following study, the CoMP-JP strategy with full coordination and per-BS power constraints is evaluated using the conventional precoding structure defined in 5.2.2.2 ('SVD-based' solution). The cases where modulation constraint is imposed ('MCS: 64QAM 4/5' in legend) and not, are evaluated. CoMP-JP strategies are compared to a MU-MIMO technique without coordination of the BSs under SR criterion ('No coordination SR' in legend).

The system bandwidth efficiency is taken from Table 7: 0.67 for the non-coordinated case. However when BSs coordinate their transmissions, a higher overhead is necessary to report the CSI from all the links BS-UE, because for the CoMP-JP all BSs contribute in the transmission of a specific user. In other words, the bandwidth efficiency due to the dedicated and common controls channels in 5.4.2 would be 0.83. And the total bandwidth efficiency for CoMP-JP here considered is: 0.6.

When modulation constraints are imposed, the spectral efficiency for each transmission mode of each users has been upper limited following the expression in (69). Consequently, the maximum cell-edge and cellular spectral efficiency that can be achieved are given by the LTE-A MCSs that can achieve a higher rate: 64QAM and code rate 4/5. At most we can achieve 4.8bits/s/Hz per user in the case with \( n_T=1 \), from which a 40\% is destined to overheads. Then, the maximum transmission rate per user is 0.6 x 4.8bits/s/Hz = 2.88bits/s/Hz. If considering 6 UEs per macrocell, it means 2 UEs per cell, the maximum cellular spectral efficiency that can be achieved is given by: 2UEs/cell x 2.88bits/s/Hz/UEs = 5.76bits/s/Hz/cell. Those maximum values are plotted in the figures with black lines. The system cannot support higher spectral efficiencies.

Figure 19 displays cell-edge spectral efficiency vs. cellular spectral efficiency (see computation details in Annex D) in Topology A (without inter-macrocell interference). Figure 20 displays cell-edge spectral efficiency vs. cellular spectral efficiency in Topology B (with inter-macrocell interference).

We can observe that significant gains are also obtained when limiting the transmission rate, both in spectral efficiency and cell-edge spectral efficiency, in the CoMP-JP strategies over the non-coordinated BS transmissions, due to the cooperation of the BSs. The gains are also remarkable for ISD higher than 500 meters, although the inter-cell interference is reduced in the non-coordinated transmission due to the path-loss effects. In the non-coordinated transmissions, the cell-edge spectral efficiency is 0 even when we do not consider the inter-macrocell interference, as only one BS is serving each user and then the system can be affected by the rank of individual channels.

Notice that higher order modulation and coding schemes are needed for low ISD, since the difference is higher between the results without and with MCS constraints ('MCS 64QAM 4/5' in figures) for low ISD than for high ISD.

When we do not consider the inter-macrocell interference (Topology A), we can observe that for ISD equal to 500 and 1000 meters the system is working at his maximum efficiency. When inter-macrocell interference is evaluated (Topology B), the system is not working in any case at his maximum efficiency.

For ISD where the system is not working at his maximum efficiency, the spectral efficiency is also reduced. But, it is important to note that in those cases, the cell-edge spectral efficiency increases compared to the case when no modulation constraints are imposed. This behaviour is due to the power loading, as it can adapt the power allocated to serve the deprived users (those with bad quality channel). Meanwhile in the cases where no modulation constraints were imposed, this power was allocated to enhance the rate of all the users.
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Figure 19: Cell-edge spectral efficiency vs. cellular spectral efficiency in CoMP-JP full coordination when per-BS power constraint applying and not modulation constraints, with Topology A. ISD are 500m(black), 1000m(blue), 1500m(red) and 2000m(green).

Figure 20: Cell-edge spectral efficiency vs. cellular spectral efficiency in CoMP-JP full coordination when per-BS power constraint applying and not modulation constraints, with Topology B. ISD are 500m(black), 1000m(blue), 1500m(red) and 2000m(green).
6 COORDINATED MULTIPOINT IN RELAY TRANSMISSIONS

A half-duplex relay station (RS)-based cellular system deployment is considered where multiple base stations (BSs) cooperate in the BS-RS in-band transmission for the downlink. A MIMO-OFDM system is considered with $N$ orthogonal subcarriers. A downlink transmission setup is adopted where $B$ BSs coordinate their transmissions and are assisted by $R$ RSs to transmit messages to $K$ UEs. Each BS has $N_B$ transmit antennas, while each RS has $N_R$ receive and transmit antennas and each UE has $N_M$ receive antennas.

With the joint optimization of the precoders and the power allocated to the wireless backhaul (BS-RS link) and to the RS-UE access, it is possible to exploit the benefits of CoMP-JP along with combating the pathloss and shadowing effects.

In the following section 6.1 the characteristics of a relay transmission with half-duplex relay terminals are detailed. With those characteristics, different transmission strategies for each link are proposed and evaluated; the signal model and access scheme on the BS-RS link and on the RS-UE link is described in sections 6.2 and 6.3, respectively. The whole problem is shown to be convex under conventional QoS objective functions in section 6.4. Two sub-optimal and low complexity solutions are proposed and evaluated in section 6.5, where the resource allocation is done independently by allocating the power in the BS-RS link and after adapt the transmission time in the RS-UE link.

In section 6.6, the duration of the relay-receive and the relay-transmit phases is fixed beforehand, so that the interference induced by other cells is stationary during a transmission interval. A simple and efficient algorithm to allocate power on the BS-RS link is proposed and developed, whose solution has a significantly reduced complexity: the number of variables to be optimized turns out to be independent on the number of transmission modes, thus making it easily amenable to multicarrier systems.

6.1 Half-duplex relay transmissions

A relay transmission where Relay Stations (RSs) are half duplex terminals is assumed. So, RSs cannot receive and transmit simultaneously on the same time or frequency band. The RS operation where the BS-RS link shares the same carrier frequency than the RS-UE links is called inband-relaying.

Therefore, at least two time slots are required to deliver a message from the source (BS) to the destination (UE). These time slots correspond to the relay-receive phase (1st hop) and relay-transmit phase (2nd hop), as it is represented in Figure 21.

![Figure 21](image)

**Figure 21:** Time slots required in a relay transmission with half duplex RS sharing the same frequency band.

It is assumed that RSs operate under Decode-and-Forward (DF) protocol. This decoding role consists on RS decoding the message received from the BS in the first hop, and re-encoding and transmitting it to the UE in the second hop. DF is a suitable coding approach for BS-RS links where high SNR is expected if LOS propagation is met [30]. Moreover, it is also assumed simple forwarding relaying protocol, so UE only process the signals transmitted by the RS and do not process the signals from the BSs.
In relay transmissions the maximum transmission rate is obtained when the durations of the slots ($\alpha$, $1-\alpha$) is optimized. And, the user’s transmission rate is given by the minimum between the rates in the first and in the second hop, by the following way:

$$R_{\text{relayed}} = \max_{\alpha} \min \left( \alpha C_{\text{BS-\text{RS}}} \left(1-\alpha \right) C_{\text{RS-\text{MS}}} \right)$$

which can also be expressed, for the optimum durations of the time slots $\alpha$, in terms of the capacities in the first and second hop:

$$R_{\text{relayed}} = \frac{C_{\text{BS-\text{RS}}} C_{\text{RS-\text{MS}}}}{C_{\text{BS-\text{RS}}} + C_{\text{RS-\text{MS}}}} = \frac{1}{C_{\text{BS-\text{RS}}}} + \frac{1}{C_{\text{RS-\text{MS}}}}$$

Consequently, $R_{\text{relayed}}$ is an increasing function of $C_{\text{BS-\text{RS}}}$ and $C_{\text{RS-\text{MS}}}$. The capacity in the second hop $C_{\text{RS-\text{MS}}}$ is enhanced as the RS is nearer the UE.

To improve the capacity on the first hop $C_{\text{BS-\text{RS}}}$, it is assumed that RSs are placed in specifically planned positions above root-tops or in lampposts, ensuring the Line-Of-Sight (LOS) propagation conditions with the BSs. But, at the same time that the RS is in LOS with its serving BS, it is likely that other sources were also in LOS with the RS, which could limit the capacity as the observed interference would be very high.

For that reason, CoMP is a suitable approach for the first hop, as it quite reduces the interference from coordinated sources (the inter-cell interference) and provides the MU-MIMO capacity gains.

### 6.2 Signal model and access scheme on the BS-RS link

On the first hop $B$ BSs with $n_B$ transmit antennas coordinate their transmissions to transmit to $R$ RSs with $n_R$ receive antennas. A fixed fraction of time $\alpha_i$ is devoted for the transmission in the first hop (see Figure 21).

Different downlink transmission strategies based on Coordinated multi-point (CoMP) are performed on the first hop (BS-RS link). CoMP transmission and reception is a network multiple-input multiple-output (MIMO) technology considered in 3GPP LTE-Advanced systems, which utilizes coordination and/or cooperation among neighboring cells to improve coverage, cell-edge capacity and system spectral efficiency. Two different approaches for CoMP are considered:

- Joint Processing (CoMP-JP)
- Coordinated Scheduling/Beamforming (CoMP-CS/CB)

With CoMP-JP, signals designated for a single RS are simultaneously transmitted from multiple neighboring BS. These BS cooperate in order to work as a single transmitter with geographically separated transmit antennas. It is considered that BS transmit simultaneously to multiple $R$ RSs in the macrocell following the CoMP-JP full coordinated strategy detailed in section 5.1.1, and hence improved system efficiency can be achieved. CoMP-JP has the benefit that, when used in conjunction with the BD-ZF (Block Diagonalization and Zero-Forcing) algorithm, it resolves the interference created by the strongest BS interferers to the MBS-RS links. This way, the inter-cell interference can be reduced.

CoMP-JP is appropriate for the BS-RS links for many reasons:

- LOS propagation conditions require aggressive interference management, and CoMP-JP is able to combat efficiently the interference from coordinated sources,
- high SNR is expected in the BS-RS links and then we can obtain full advantage of multiplexing gains,
- long time coherence is expected in the BS-RS links (as both, BS and RS terminals, have static positions) and hence full CSIT is available at the BSs and we can apply the power loading needed for the CoMP-JP.

When CoMP-JP is applied in the first hop, the system is unaffected by the rank of individual channels as each RS is served by more than one BS, and the probability of the channel to be rank deficiently is very low (more details are given in section 6.2.1). Moreover, CoMP-JP allows deleting the inter-cell interference, due to the cooperation of the BSs.

![Diagram of Access modes based on CoMP for relay transmissions in 4G systems](image)

**Figure 22:** Access modes considered in the first hop. CoMP-JP (left) or CoMP-CS/CB (right): BF-TDMA or BD-ZF.

With CoMP-CS/CB, RS scheduling and beamforming are dynamically coordinated among neighboring BS in order to control and reduce the interference among different transmissions. However, no cooperation between BSs is considered and the BSs only coordinate the beamformers. One way to control the inter-cell interference is by orthogonalizing BS transmissions in time.

Different approaches of CoMP-CS/CB can be used:

- *Beamforming-TDMA* (BF-TDMA): where each BS serves its associated RSs under round-robin TDMA, and BS transmissions are orthogonal in time. As one slot per BS transmission is allocated, inter-cell interference is not created. Moreover, as each BS allocates one slot for each BS-RS link, intra-cell interference is also deleted (see Figure 22). This technique requires coordination between the BSs, since BSs transmissions have to be synchronized in time.
- **Block Diagonalization – Zero Forcing (BD-ZF)**: where each BS serves its associated RSs following a MU-MIMO technique based on BD-ZF. BD-ZF is able to delete the intra-cell interference as the precoding matrices are obtained from the null space of the other RSs in the same cell. Moreover, to deal with inter-cell interference, BSs transmissions need to be orthogonal in time. Coordination between the BSs is needed to synchronize the BSs transmissions (see Figure 22).

Techniques based on CoMP-CS/CB have lower requirements in backhaul bandwidth than CoMP-JP -as no cooperation between the BSs is needed-. Even though the system can be affected by the rank of individual channels, since each RS is only served by one BS.

### 6.2.1 CoMP-JP on the first hop

Let us consider that all BSs transmit on a fixed fraction of time $\alpha_l$ on the first hop to the RSs following a CoMP-JP strategy based on BD-ZF [27] (see Figure 22), which is appropriate for BS-RS links in LOS conditions (MUEE precoding provides improved performance only at low SNR[28]).

The signal transmitted on the $l$-th subcarrier by all $n_R\times B$ antennas is given by

$$\mathbf{x}^l = \sum_{i=1}^{n_l} \mathbf{Q}_i^l \mathbf{b}_i^l \in \mathbb{C}^{n_R \times 1} \quad l = 1, \ldots, N$$

(72)

where $\mathbf{b}_i^l$ is the symbol stream with $m_i$ components associated to the $l$-th subcarrier of the $i$-th RS, and $\mathbf{Q}_i^l$ is its associated precoding matrix. We adopt a conventional BD-ZF precoding [14] defined by three matrices,

$$\mathbf{Q}_i^l = \mathbf{V}_i^l \mathbf{W}_i^l \mathbf{P}_i^l \quad i = 1, \ldots, R \quad l = 1, \ldots, N$$

(73)

where $\mathbf{P}_i^l$ is a diagonal matrix describing the power allocated per symbol stream $\mathbf{b}_i^l$, while $\mathbf{V}_i^l$ is the $Bn_R \times Bn_R - (R-1)n_R$ BD-ZF precoding matrix detailed in section 5.1.1 for CoMP-JP full coordination.

By virtue of the ZF precoding, the signal received on the $l$-th subcarrier by the $i$-th RS is affected by the $n_R \times B - n_R$ channel matrix $\mathbf{H}_i^l$ (containing the channel gains on the $l$-th subcarrier between the transmitting antennas at the $B$ BSs and its receiving antennas):

$$\mathbf{y}_i^l = \mathbf{H}_i^l \left( \mathbf{V}_i^l \mathbf{W}_i^l \mathbf{P}_i^l \mathbf{b}_i^l + \sum_{j=1, j \neq i}^{R} \mathbf{V}_j^l \mathbf{W}_j^l \mathbf{P}_j^l \mathbf{b}_j^l \right) + \mathbf{n}_i^l \in \mathbb{C}^{n_R \times 1} \quad i = 1, \ldots, R \quad l = 1, \ldots, N$$

(74)

Regarding matrix $\mathbf{W}_i^l$, if we decide to maximize the transmission rate, its optimal design has been derived in [35] when individual power constraints per BS are considered (see section 5.2.2). However, in the relayed CoMP-JP case, the improvement over SVD-based precoding (see section 5.2.1 and 5.2.2.2) is modest at the expenses of increasing the computational complexity. Consequently, we define $\mathbf{W}_i^l$ as the matrix containing the $m_i$ right singular vectors of $\mathbf{N}_i^{R/2} \mathbf{H}_i^l \mathbf{V}_i^l$ associated to the largest singular vectors.

The BD-ZF precoder design requires $\mathbf{V}_i^l \in \text{kernel}(\mathbf{H}_i^l)$, where:

$$\mathbf{\tilde{H}}_i^l = \begin{bmatrix} \mathbf{H}_i^T & \cdots & \mathbf{H}_{i-1}^T & \mathbf{H}_{i+1}^T & \cdots & \mathbf{H}_R^T \end{bmatrix} \quad i = 1, \ldots, R \quad l = 1, \ldots, N$$

(75)

The existence of the kernel requires number of rows is lower than number of columns $Bn_R > (R-1)n_R$, and hence:

$$\text{rank}(\mathbf{H}_i^l \mathbf{V}_i^l) \leq \min(n_R, Bn_R - (R-1)n_R)$$

Additionally, symbol decidability at the receivers requires
If this condition is not met, one may decide to either reduce the values of $m_i^l$, or to split the first hop slot in subslots and serve the RS orthogonally in time, so that on each subslot the conditions (76) are met. This comes at the price of efficiency loss.

It must be remarked that in the eventual case the $i$-th RS observes all coordinated BSs in LOS (hence BS-RS link channels are rank deficient) the rank of $\mathbf{H}_i^l$ grows up to full-rows rank, since channels to the $B$ BSs are linearly independent with probability 1.

Once $\mathbf{W}_i^l$ has been selected, the achievable rate for messages intended to the $i$-th RS becomes:

$$ r_i = \frac{1}{N} \sum_{i=1}^{N} \log_2 \left( 1 + \frac{1}{\lambda_i^l} \right) $$

$$ = \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{m} \log_2 \left( 1 + p_j^l \left( \lambda_i^l \right)^2 \right) \quad i = 1,...,R $$

where $\mathbf{A}_i^l = \text{diag}(\lambda_i^l, ..., \lambda_{i_{\text{lim}}}^l)$ contains the singular values of $\mathbf{N}_i^{l/2} \mathbf{H}_i^l$ (being $\mathbf{N}_i^l$ the correlation matrix of the noise plus interference at the receiver) and $\mathbf{P}_j^l = \text{diag}(p_j^l, ..., p_{i_{\text{lim}}}^l)$.

Moreover, when applying the modulation constraints given by the MCS, we have to upper limit the rate on the first hop for each transmission mode of each user. That is, from equation (69) and (77):

$$ r_{ij} = \min \left( \log_2 \left( 1 + p_j^l \left( \lambda_i^l \right)^2 \right), S_{\text{max}} \right) \quad i = 1,...,R \quad j = 1,...,m_i \quad l = 1,...,N $$

where $S_{\text{max}}$ is the maximum achieved spectral efficiency for the LTE-A MCS, defined in 5.4.2.

As we are interested in allocating the power on the first hop, equation (78) can be replaced by the following constraint:

$$ \log_2 \left( 1 + p_j^l \left( \lambda_i^l \right)^2 \right) \leq S_{\text{max}} $$

Finally, the total power transmitted by the $k$-th BS is given by:

$$ P^k = \sum_{i=1}^{N} \text{tr} \mathbf{E} \left[ \mathbf{x}_i^{lH} \mathbf{x}_i^l \right] = \sum_{i=1}^{N} \text{tr} \sum_{i=1}^{R} \mathbf{W}_i^l \mathbf{P}_i^l \mathbf{W}_i^l^H = \sum_{i=1}^{N} \sum_{i=1}^{m} \sum_{i=1}^{p_j^l} \mathbf{W}_i^l \mathbf{W}_i^l^H = \sum_{i=1}^{N} \sum_{i=1}^{m} \sum_{i=1}^{p_j^l} \mathbf{W}_i^l \mathbf{W}_i^l^H $$

where $\mathbf{x}_i^l$ is the signal transmitted on the $l$-th subcarrier by the $k$-th BS and $\mathbf{W}_i^l$ contains the $n_B$ rows of $\mathbf{W}_i^l$ used by the $k$-th BS in the transmission of message to the $i$-th RS and $\mathbf{W}_i^l^H$ is the $j$-th column of $\mathbf{W}_i^l$.

### 6.2.2 CoMP-CS/CB on the first hop

Let us considerer that each BS transmit on a fixed fraction of time $\alpha_{ik}$ on the first hop to the ind-cell RS following a CoMP strategy based on BD-ZF. When $\alpha_{ik}$ is fixed, it satisfies: $\alpha_{ik} = \alpha_i / B$ (where $\alpha_i$ is the time devoted for the transmissions in the BS-RS link). Otherwise, they must satisfy (see Figure 22):

$$ \alpha_i = \sum_{k=1}^{B} \alpha_{ik} $$
The signal transmitted on the \( l \)-th subcarrier by \( k \)-th BS with \( n_B \) antennas is given by:

\[
x'_k = \sum_{i=1}^{R_k} Q_{ik}^l b_{ik}^l \in \mathbb{C}^{n_B \times 1} \quad k = 1,...,B \quad l = 1,...,N
\]  

(81)

where \( b_{ik}^l \) is the symbol stream with \( m_{ik}^l \) components associated to the \( i \)-th RS and the \( l \)-th subcarrier, and \( Q_{ik}^l \) is its associated precoding matrix. \( R_k \) refers to the number of RS served by the \( k \)-th BS, which is related with the total number of RS in the macrocell as:

\[
R = \sum_{k=1}^{B} R_k
\]

We adopt a conventional BD-ZF precoding defined by three matrices,

\[
Q_{ik}^l = V_{ik}^l W_{ik}^l P_{ik}^l \quad i = 1,...,R_k \quad k = 1,...,B \quad l = 1,...,N
\]

(82)

where \( P_{ik}^l \) is a diagonal matrix describing the power allocated per symbol stream \( b_{ik}^l \), while \( V_{ik}^l \) is the \( n_B \times (n_R - (R_k - 1) - n_B) \) BD-ZF precoding matrix.

By virtue of the ZF precoding, the signal received by the \( i \)-th RS at the \( l \)-th subcarrier in the \( k \)-th cell is affected by the \( n_B \times n_B \) channel matrix \( H_{ik}^l \) (containing the channel gains at the \( l \)-th subcarrier between the transmitting antennas at the BS and its receiving antennas):

\[
y_{ik}^l = H_{ik}^l \left( V_{ik}^l W_{ik}^l P_{ik}^l b_{ik}^l + \sum_{j=1, j \neq i}^{R_k} V_{ik}^l W_{ik}^l P_{ik}^l b_{ik}^l \right) + n_{ik}^l \in \mathbb{C}^{n_B \times 1}
\]

(83)

Regarding matrix \( W_{ik}^l \) it is obtained from the \( m_{ik}^l \) right singular vectors of \( N_{ik}^{(l-1)/2} H_{ik}^l V_{ik}^l \) associated to the largest singular vectors. \( m_{ik}^l \) denotes the number of symbol streams associated to the \( l \)-th subcarrier of the \( i \)-th RS in the \( k \)-th cell.

The BD-ZF precoder design requires \( V_{ik}^l \in \text{kernel}(H_{ik}^l) \), where:

\[
\tilde{H}_{ik}^l = \left[ H_{ik}^l H_{i-1,k}^l \ldots H_{i-1,1}^l H_{i+1,k}^l \ldots H_{R_k,k}^l \right]^T
\]

(84)

The existence of the kernel requires number of rows is lower than number of columns \( n_B > (R_k - 1) n_B \), and hence:

\[
\text{rank}(\tilde{H}_{ik}^l V_{ik}^l) \leq \min\left(n_k n_B - (R_k - 1) n_B\right)
\]

Additionally, symbol decidability at the receivers requires

\[
\sum_{i=1}^{R_k} m_{ik}^l \leq n_B \quad m_{ik}^l \leq \text{rank}(\tilde{H}_{ik}^l V_{ik}^l) \quad i = 1,...,R_k \quad k = 1,...,B \quad l = 1,...,N
\]

(85)

Once \( W_{ik}^l \) has been selected, the achievable rate for messages intended to the \( i \)-th RS served by the \( k \)-th BS becomes:

\[
r_{ik} = \frac{1}{N} \sum_{l=1}^{N} \log_2 \left| I + E \left[ y_{ik}^l y_{ik}^l \right]^T \right| = \frac{1}{N} \sum_{l=1}^{N} \log_2 \left| I + A_{ik}^l P_{ik}^l A_{ik}^l \right| = \frac{1}{N} \sum_{l=1}^{N} \sum_{j=1}^{m_{ik}^l} \log_2 \left( 1 + \lambda_{ij}^2 p_{ij}^l \right)
\]

(86)

where \( A_{ik}^l = \text{diag}(\lambda_{ik1}^l, \ldots, \lambda_{ikm_{ik}^l}) \) contains the singular values of \( N_{ik}^{(l-1)/2} H_{ik}^l V_{ik}^l \) (being \( N_{ik}^l \) the correlation matrix of the noise plus interference at the receiver) and \( P_{ik}^l = \text{diag}(p_{ik1}^l, \ldots, p_{ikm_{ik}^l}) \).

When applying the modulation constraints, we have to upper limit the transmission rate on the first hop for each transmission mode of each user. That is:
\[ r_{ikj}^l = \min \left( \log_2 \left( 1 + \lambda_{ikj}^l \cdot p_{ikj}^l \right), S_{\text{max}} \right) \quad i = 1, \ldots, R, \quad k = 1, \ldots, B, \quad j = 1, \ldots, m, \quad l = 1, \ldots, N \quad (87) \]

where \( S_{\text{max}} \) is the maximum achieved spectral efficiency for the LTE-A MCS (see section 5.4.2). Equation (87) can be replaced by the following restriction:

\[ \log_2 \left( 1 + \lambda_{ikj}^l \cdot p_{ikj}^l \right) \leq S_{\text{max}} \quad (88) \]

Finally, the total power transmitted by the \( k \)-th BS is given by:

\[ P^k = \sum_{i=1}^{N} \text{tr} \left\{ x_i^j x_i^j H \right\} = \sum_{i=1}^{N} \text{tr} \sum_{j=1}^{R} v_{ik}^j w_{ik}^j p_{ik}^j w_{ik}^j H v_{ik}^j H = \sum_{i=1}^{N} \text{tr} \sum_{j=1}^{R} p_{ik}^j = \sum_{i=1}^{N} \sum_{j=1}^{R} \sum_{l=1}^{m} p_{ik}^l \quad (89) \]

where \( x_i^j \) is the signal transmitted on the \( l \)-th subcarrier by the \( k \)-th BS and the property \( \text{tr} AB = \text{tr} BA \) is used.

### 6.3 Signal model and access scheme on the RS-UE link

On the second hop, each RS transmits to its associated UE on a fixed fraction of time \( \alpha_s = 1 - \alpha_r \). Each UE is associated to a single RS in a given time and frequency. RSs transmissions are not coordinated in the way BSs transmissions are: their transmissions are either interfered (if multiple RSs transmit simultaneously in time) or orthogonalized (if we allocate one time slot per RS transmission). So, subframe \( \alpha_c \) can be split over \( F \) time slots (being \( F \) an integer submultiple of \( R \) of durations \( \alpha_{s1}, \ldots, \alpha_{sF} \) (see Figure 23). On each time slot, RIF relays can transmit. In this way we reduce interference at the expenses of some loss in spectral efficiency.

Each RS transmits to a single associated UE and therefore it is considered as a single user (possibly interfered) MIMO link. Full CSIT may be exploited at the RS if sufficient feedback rate from the UE is allowed. However, we do not consider sufficient feedback rate in the RS-UE link and hence only average CSIT is assumed. Even if coding is done across multiple states channel (as in a multicarrier case) and interference is white, the maximum rate is given by the MIMO ergodic capacity, for which exact expressions are known [31].

As we are assuming no coordination among RSs, only single user MIMO transmissions can be appointed. The achievable rate for each RS-UE link, \( r_2 \), follows the conventional MIMO capacity expression for an OFDM system, affected by the presence of interference from other RS transmissions:

\[ r_{2iq} = \frac{1}{N} \sum_{i=1}^{N} r_{2iq}^i = \frac{1}{N} \sum_{i=1}^{N} \log_2 \left| I + \frac{P_{iq}^R}{N n_R} H_{ii}^H H_i^i \left( N_i^i + \sum_{j=1, j \neq i}^{R} \frac{P_{jq}^R}{N n_R} H_{jj}^H H_j^j \right)^{-1} \right| \quad (90) \]

where \( i = 1, \ldots, R, \quad q = 1, \ldots, F \); \( r_{2iq}^i \) denotes the rate in the \( i \)-th RS-UE link, which has been scheduled in timeslot \( q \); \( r_{2iq}^l \) denotes the rate on the \( l \)-th subcarrier of the \( i \)-th RS-UE link; \( P_{iq}^R \) is the power transmitted by the \( i \)-th RS in the \( q \)-th time slot to its UE and \( P_{jq}^R \) defines the power transmitted by the \( j \)-th RS on the same time slot; and \( N_i^i \) is the correlation of the noise plus interference in the \( l \)-th subcarrier of the \( i \)-th RS-UE link.

In order to adapt the transmission rate to the modulation and coding schemes (MCSs), we have to apply the modulation constraint to upper limit the transmission rate of each user on each subcarrier frequency:

\[ r_{2iq}^l \leq S_{\text{max}} n_M \quad (91) \]

where \( S_{\text{max}} \) is the maximum spectral efficiency achieved by the LTE-A MCS (defined in 5.4.2) and \( n_M \) is the number of receive antennas at the \( i \)-th UE.

When \( F = R \) (hence, interference is avoided at RS transmissions), the best solution is set \( P_{iq}^R \) equal to the maximum allocated power on each RS (\( P_{\text{max}}^R \)). Otherwise, when \( F < R \) we can adapt the power transmitted by each RS in such a way that the interference generated to other UE on
q-th time slot is reduced and jointly $r_{2i_q}$ increases. To that end, we propose the following optimization for each q-th time slot:

$$\begin{align*}
\text{minimize} \quad & - f \left( r_{21q}, \ldots, r_{2Rq} \right) \\
\text{s.t.} \quad & P_{iq}^R \geq 0 \quad i = 1, \ldots, R
\end{align*}$$

(92)

which would be set, when applying modulation constraints, by the following way:

$$\begin{align*}
\text{minimize} \quad & - f \left( r_{21q}, \ldots, r_{2Rq} \right) \\
\text{s.t.} \quad & P_{iq}^R \geq 0 \quad i = 1, \ldots, R \\
& r_{2i_q} \leq S_{\text{max}} n_{st} \quad i = 1, \ldots, N
\end{align*}$$

(93)

The problems in (92) and (93) are not convex in $P_{iq}^R$ even for concave target functions $f(.)$ due to the presence of $P_{iq}^R$ as interference in (90). However, it is sure that there is a better option than all RSs transmitting at $P_{\text{max}}^R$, which can be obtained by applying interior point methods [32] initializing $P_{iq}^R$ with $P_{\text{max}}^R$.

Figure 23: Access modes considered in the second hop over half-duplex relay transmissions in the downlink (B=3, R=6, F=1 and 6).

### 6.4 QoS-based resource allocation

To preserve information flow through the RSs, the rate at the i-th UE served by the i-th RS in the q-th time slot of the second hop is constrained by the minimum between rates in both hops:

$$r_i \leq \min \left( \alpha_{1i} r_{1i}, \alpha_{2i} r_{2i_q} \right)$$

(94)

where $i = 1, \ldots, R$; $q = 1, \ldots, F$; and $r_{2i_q}$ is the rate in the second hop for the i-th link RS-UE, which has been scheduled in timeslot $q$. Equation (94) can be also written as two simultaneous constraints. For the relayed CoMP-JP case:

$$\alpha_{1i} \frac{1}{N} \sum_{l=1}^{N} \sum_{j=1}^{m_l} \log_2 \left( 1 + \lambda_{lj}^2 \ P_{lj}^j \right) \geq r_i \quad \alpha_{2i} r_{2i_q} \geq r_i$$

(95)

and for the relayed CoMP-CS/CB case the nomenclature is slightly different:

$$\alpha_{ik} \frac{1}{N} \sum_{l=1}^{N} \sum_{j=1}^{m_l} \log_2 \left( 1 + \lambda_{lk}^2 \ P_{lk}^j \right) \geq r_i \quad \alpha_{2ik} r_{2i_q} \geq r_i$$

(96)
The functions in (95) and (96) are not jointly concave in $\alpha_i$ and $p_{ij}^0$ (or $\alpha_{ij}$ and $p_{ij}^0$), but the change of variable $p_{ij}^0 = t_{ij}^0 / \alpha_i$ can be plugged to convert it to the perspective function [32], which is jointly concave in $t_{ij}^0$ and $\alpha_i$.

When considering the modulation constraint imposed by restriction (79) and the previous variable change ($p_{ij}^0 = t_{ij}^0 / \alpha_i$), the restriction turns out to be not jointly concave in $t_{ij}^0$ and $\alpha_i$. But, we can convert it to a concave function in $t_{ij}^0$ and $\alpha_i$ by developing the expression, which results into an affine inequality over both variables:

$$t_{ij}^0 \leq \alpha_i \frac{(2^{b_{\text{max}}^0} - 1)}{(\bar{\lambda}_{ij}^0)^2} \tag{97}$$

We are interested in allocating resources while maximizing some global function $f(r)$ measuring system performance, where vector $r$ contains the rates $r_i$ for all pairs RS-UE. Note that the restrictions imposed by the information flow at the RS (in (94)), the modulation constraint (in (79)), the sum of the time durations of each hop and the per-BS transmitted power (in (80)) are formulated as convex inequalities or affine equalities. Hence, we should select a meaningful differentiable concave function in $f(r)$ so that the overall problem is convex and we can fully exploit its properties. Convenient choices are the weighted sum of rates or the geometric mean.

Gathering the equations above, the optimization problem—for the relayed CoMP-JP case— is formulated as:

$$\text{minimize} \quad -f(\{r_i\})$$

$$\text{s.t.} \quad \begin{cases} r_i - \alpha_i \frac{1}{N} \sum_{l=1}^{N} \sum_{j=1}^{m_l} \log_2 \left( 1 + \frac{(\bar{\lambda}_{ij}^0)^2 t_{ij}^0}{\alpha_i} \right) \leq 0 & i = 1, \ldots, R \\ r_i - \alpha_{2q} r_{2q} \leq 0 & i = 1, \ldots, R \\ \sum_{l=1}^{N} \sum_{i=1}^{B} t_{ij}^0 \delta_{ij}^{\text{RS}} - \alpha_i p_{\text{max}} \leq 0 & k = 1, \ldots, B \\ \alpha_i + \sum_{q=1}^{r} \alpha_{2q} = 1 \\ t_{ij}^0 - \alpha_i \frac{(2^{b_{\text{max}}^0} - 1)}{(\bar{\lambda}_{ij}^0)^2} \leq 0 & i = 1, \ldots, R \quad j = 1, \ldots, m_l \quad l = 1, \ldots, N \\ -r_i \leq 0 & i = 1, \ldots, R \\ -t_{ij}^0 \leq 0 & i = 1, \ldots, R \quad j = 1, \ldots, m_l \quad l = 1, \ldots, N \end{cases} \tag{98}$$

where $\alpha_i$ and $\alpha_{2q}$ are the time allocated to the BS-RS link and the RS-UE link, respectively, $\delta_{ij}^{\text{RS}}$ is defined in equation (80) and $S_{\text{max}}$ is given by the maximum achievable spectral efficiency. The user’s transmission rate $r_i$ is given by the minimum between the rate in the first and second hop, which is expressed in (98) with the first and second constraint. Moreover, we have the per-BS power constraint, the transmission time allocation constraint, the modulation constraints and the rates and the powers allocated have to be positive. The expression for the transmission rate in the first hop, the per-BS power constraint and the transmission time allocation constraint would be slightly different in the CoMP-CS/CB (see section 6.2.2), since there are more subslots for BS transmissions and each BS only transmits to its associated RS.

Note that inequality constraints are convex and equality constraints are linear in (98), thus defining a convex problem. The definition of the max-min problem (maximization of the minimum rate) is still possible even though the minimum of the rates is not a differentiable function. We just need to reformulate equation (98) in epigraph form [32]. In any case, the problem can be solved in polynomial time using, for instance, interior point methods [32].
6.4.1 Simulation results

The evaluation of the proposed approach is done on a radio access network based on LTE-A specifications [5]. A hexagonal deployment is considered (see section 4.1) and an outdoor homogeneous scenario is deployed (see section 4.2.1), following the simulation parameters detailed in section 4.2.4. \( B = 3 \) BSs and a total of \( R = 6 \) RSs are deployed on the macrocell. On each scenario, \( M = 6 \) users are dropped uniformly in the macrocell arrangement, one assigned to each RS. All the RSs are at the same distance \( d \) to their associated BS, equal to 60% of the cell radius. The number of antennas is \( n_B = 4 \) at the BS, \( n_R = 2 \) at the RS and \( n_U = 1 \) at the UE. Inter site distances are 1000, 1500, 2000, 2500 and 3000 m. Overheads at the system level are considered from Table 7: \( \eta_B = 0.67 \) for the BS-RS link and \( \eta_{\text{BS}} = 0.71 \) for the RS-UE link.

In the following study, the optimal solution proposed in equation (98) is evaluated for the sum rate (SR) and the weighted sum rate (WSR) in \( f(\cdot) \), over 1000 random user deployments for \( F = 1 \) and \( F = 6 \) cases in the second hop. When maximizing the WSR, the weights are inversely proportional to the rate on the second hop in order to avoid unfair services to deprived users (i.e. \( \mu_i = 1/r_{2i} \)). The optimal solution given by equation (98) (‘Relayed CoMP-JP’ in legend) is compared with a relay-assisted transmission with un-cooperated BSs (‘Relayed BF-TDMA’ in legend). In this later case, the sum rate is adopted and each BS serves its associated RS under round-robin TDMA.

Next figures display cell-edge spectral efficiency \((r_{ce})\) vs. cellular spectral efficiency \((S_c)\) in Topology A (without inter-macrocell interference) and Topology B (with inter-macrocell interference), when taking into account or not the LTE-A modulation constraints. See details of the different topologies in chapter 4 and modulation constraints in section 5.4.2. Computation details of \( r_{ce} \) and \( S_c \) can be found in Annex D.

Figure 24 displays \( r_{ce} \) vs. \( S_c \) in Topology A. Figure 25 displays \( r_{ce} \) vs. \( S_c \) in Topology A when applying modulation constraints following the LTE-A MCSs.

Figure 26 displays \( r_{ce} \) vs. \( S_c \) in Topology B. Figure 27 displays \( r_{ce} \) vs. \( S_c \) in Topology B when applying LTE-A modulation constraints following the LTE-A MCSs.

It can be observed in all figures that the system performance decreases as the inter site distance (ISD) increases. However, the losses are not as remarkable as in the non relay-assisted transmissions observed in chapter 4. This fact confirms that a relay transmission is a simple and low-cost approach for cellular systems, as high inter site distances can be used and the system performance is maintained. Nevertheless, we cannot compare results from chapter 4 and 5, because for simulation results we are assuming that users are deployed uniformly in all the macrocell, while those users close to the BSs are not benefited from the RS assistance.

When comparing the simulation results on each figure, we can also observe significant gains in terms of \( S_c \) when using the CoMP-JP strategies in the first hop as compared to BF-TDMA in the first hop. It is due to the cooperation of the BSs. For \( F = 1 \), the relayed CoMP-JP strategy achieve higher results than the relayed BF-TDMA both in \( S_c \) and \( r_{ce} \). Meanwhile when \( F = 6 \) (TDMA case in the second hop), the relayed CoMP-JP strategy only achieve better results in \( S_c \), while relayed BF-TDMA achieve better results in \( r_{ce} \) because it allocates one slot for each BS-RS link and then it allows to serve all the users in the same way, even there are some loses in spectral efficiency due to the TDMA in the first hop.

When comparing the access modes in the second hop for the Relayed CoMP-JP case, it can be observed that the case \( F = 1 \) performs better than the case \( F = 6 \). It is mainly for two reasons. Firstly, when \( F = 1 \) all the users are served simultaneously in all the time devoted for the second hop and then there is no loss in spectral efficiency due to the TDMA (as happens in the \( F = 6 \) case). Secondly, thanks to the optimization of the power transmitted by the RSs in the second hop for the interference case (detailed in section 6.3), the transmission rates in the second hop can be increased by controlling the interference from other RSs transmissions.

The differences provided by using different objective functions are remarkable in all figures. When the SR is used as the objective function, we observe greater values in the spectral efficiency.
than using the WSR whereas using the WSR improves the outage of the system at the cost of losing spectral efficiency. In terms of $r_{out}$, the SR performs poorly unless we force service to all users in the second hop by choosing $F = 1$.

Figure 24: Cell-edge spectral efficiency vs. cellular spectral efficiency for different transmission strategies on the first hop (CoMP-JP, BF-TDMA) and access modes on the second hop (F=1, 6) in Topology A. ISD are 1000m(black), 1500m(blue), 2000m(red), 2500m(magenta) and 3000m(green).

Comparing Figure 24 (results without modulation constraints) and Figure 25 (results with modulation constraints), it can be observed that the $S_e$ is reduced, because the modulation constraints upper limit the rate of each transmission mode. Therefore, the performance of relay transmission schemes might be improved if a higher order constellation were adopted. On the other side, $r_{ce}$ is not so affected by the modulation constraints in the relayed CoMP-JP strategies.
since, due to the power loading, the power allocated can be adapted to serve the deprived users (those with bad quality channel). Even though, it does not happen in the relayed BF-TDMA strategy, as it makes the power loading for each individual user. And, for that reason, the results with relayed BF-TDMA when applying modulation constraints are reduced in a higher way than when we use CoMP-JP in the first hop. This behaviour is also presented in simulation results for Topology B.

![Graph](https://example.com/graph.png)

**Figure 26:** Cell-edge spectral efficiency vs. cellular spectral efficiency for different transmission strategies on the first hop (CoMP-JP, BF-TDMA) and access modes on the second hop (F=1, 6) in Topology B. ISD are 1000m(black), 1500m(blue), 2000m(red), 2500m(magenta) and 3000m(green).

![Graph](https://example.com/graph2.png)

**Figure 27:** Cell-edge spectral efficiency vs. cellular spectral efficiency for different transmission strategies on the first hop (CoMP-JP, BF-TDMA) and access modes on the second hop (F=1, 6) in Topology B with modulation constraints. ISD are 1000m(black), 1500m(blue), 2000m(red), 2500m(magenta) and 3000m(green).

When comparing simulation results in Topology A (Figure 24 and Figure 25) and Topology B (Figure 26 and Figure 27), it can be observed that the inter-macrocell interference strongly...
affect on the cellular spectral efficiency. Actually, the inter-macrocell interference level received in the RSs in the first hop is very high, as BSs transmit at its maximum allocated power. Moreover, users on the cell-edge are strongly affected by the inter-macrocell interference as it was demonstrated on 5.1.4.

Next Figure 28 display the cumulative density function (cdf) for the values of $\alpha_1$ in statistically independent scenarios when adopting WSR and the SR criteria for $f(.)$ and $F=1$, in Topology A (left figure) and Topology B (right figure).

It can be observed that the optimum $\alpha_1$ in terms of spectral efficiency is a random variable that depends on the particular scenario and the target function to be maximized. As WSR is more concerned about users having bad quality channel in the RS-UE link (those requiring more transmission time in the second hop) lower values of $\alpha_1$ are observed. When taking into account the inter-macrocell interference (Topology B), higher values of $\alpha_1$ are observed because the inter-macrocell interference strongly affects the first hop transmission and more time is required for the transmissions in the first hop.

**Figure 28:** Cumulative density function (cdf) of the values of $\alpha_1$ for WSR and SR criteria with $F=1$, in Topology A (left) and Topology B (right). ISD is 1500m.

Next Figure 29 shows the cumulative density function of the cellular spectral efficiency achieved in the second hop when interference in the second hop is created ($F=1$), in statistically independent scenarios for Topology A and B, when taking into account the modulation constraints (‘64QAM 4/5’ in legend) and not.

**Figure 29:** Cumulative density function (cdf) of the cellular spectral efficiency in the second hop in both topologies A and B with $F=1$, considering modulation constraints and not. ISD is 1500m.
Cellular spectral efficiency in the second hop is defined as the sum of the transmission rate of the RSs (\( r_{2q} \)) in the one cell, and as each macrocell has three cells it is computed as the sum of the RSs in all the macrocell divided by the number of cells per macrocell:

\[
S_{c2} = \frac{1}{3} \sum_{i=1}^{r} r_{2qi}
\]

When taking into account the inter-macrocell interference (‘Topology B’ in legend), lower cellular spectral efficiencies in the second hop are observed due to the increased interference power received (see Figure 29).

When applying modulation constraints, it can be observed that the higher values of the cellular spectral efficiencies in the second hop are limited to the value given by the 64QAM 4/5 MCS: 4.8bits/s/Hz/RS×2RS/cell×0.71=6.82bits/s/Hz/cell. Where 0.71 is the overhead corresponding to the bandwidth efficiency for the link RS-UE with \( n_R=2 \) transmit antennas and \( n_M=1 \) receive antenna (see Table 7 for overhead details).

In the following we would like to analyze the total power efficiency of our system for the cases where the transmitted power at the relays is optimized, as it was considered in previous results, and in the case where RSs transmit at full power for \( F=1 \). In the case where the transmitted power at the relays is optimized, the optimization in the second hop is done following the maximization problems in (92) and (93). Notice that by optimizing the transmitted power at RSs, we transmit less power than when all the RSs transmit at their maximum power and, moreover, we can achieve higher spectral efficiencies in the second hop.

In order to fairly compare all cases, we define power efficiency as:

\[
\xi_{ef} = \frac{1}{P} \sum_{i=1}^{R} r_i \quad [\text{bps/Hz/Watt}]
\]

where, due to half duplexing of the RS, the total power consumption of the system is defined as follows:

\[
P = \alpha_1 \sum_{k=1}^{B} P_k + \alpha_2 \sum_{i=1}^{R} P_i
\]

Figure 30 shows the cumulative density function (cdf) of \( \xi_{ef} \) when WSR or SR criteria are adopted, both with \( F=1 \). It can be observed that by optimizing the transmitting power at RSs, \( \xi_{ef} \) is nearly doubled: achievable user’s transmission rate is higher and the system power consumption is lower.

**Figure 30:** Cumulative density function (cdf) of power efficiency for a ISD of 1500 m when RS transmits with less or equal to its maximum allocated power.
6.5 Uncoupled power allocation and transmission time solutions

A particular case of the problem in section 6.4 (see equation (98)), is shown next that is suitable for sub-optimal and yet simpler solutions. If $F = R$, then there are enough degrees of freedom in our problem to allocate power in the first hop and then allocate transmission time in the second hop independently [20].

More specifically, if the weighted sum rate (WSR) is adopted for $f(.)$, the allocation of powers in the first hop may be obtained in closed form using one of the approaches detailed in next sections 6.5.1 and 6.5.2. Section 6.5.3 details the transmission time allocation, which can be set afterwards by solving a linear system of equations. Simulation results in section 6.5.4 compare the performance of these sub-optimal solutions to the optimal solution for the resource allocation.

6.5.1 Scaled-waterfilling Power Constraint (SPC)

Let us adopt a single power constraint (from equation (80)), as the sum power constraint:

$$BP_{\text{max}} \geq \sum_{l=1}^{N} \sum_{i=1}^{R} V_i W_i^l P_i^l W_i^l H_i = \sum_{l=1}^{N} \sum_{i=1}^{R} P_i^l = \sum_{l=1}^{N} \sum_{i=1}^{R} \sum_{j=1}^{m} P_i^l$$  \hspace{1cm} (99)

when maximizing the weighted sum rate [26]:

$$f(P_1,...,P_R) = \sum_{i=1}^{R} \mu_i r_i = \sum_{i=1}^{R} \mu_i \frac{1}{N} \sum_{j=1}^{m} \log_2 \left(1 + P_i^l \left(\lambda_{ij}^l\right)^2\right)$$  \hspace{1cm} (100)

The conventional waterfilling solution $P_i^l^*$ can be obtained by the following expression:

$$P_i^l^* = \left(\kappa \mu_i - \frac{1}{(\lambda_{ij}^l)^2}\right)^*$$  \hspace{1cm} (101)

where $\kappa$ is such that satisfies with equality the sum power constraint in (99). Then, the solution for the power allocation turns out to be:

$$P_i^l^* = \left(\frac{P_{\text{max}} + \sum_{l=1}^{N} \sum_{i=1}^{R} \sum_{j=1}^{m} \frac{1}{B(\lambda_{ij}^l)^2} \mu_i}{m_i \sum_{l=1}^{R} \mu_i} \right)^* - \frac{1}{(\lambda_{ij}^l)^2}$$  \hspace{1cm} (102)

As it is computed under a sum power constraint, we need to scale the powers as $P_i^l \leftarrow \kappa \cdot P_i^l^*$ so that the per-BS power constraint is met, using:

$$\kappa = P_{\text{max}} \left(\max_{k=1,...,B} \sum_{i=1}^{R} \sum_{l=1}^{m_i} \hat{W}_i^l P_i^l \hat{W}_i^l^H\right)^{-1}$$  \hspace{1cm} (103)

Therefore, the transmission rate towards the $i$-th RS is:

$$\hat{r}_i = \frac{1}{N} \sum_{l=1}^{R} \sum_{j=1}^{m_i} \log_2 \left(1 + \kappa P_i^l^* \left(\lambda_{ij}^l\right)^2\right)$$  \hspace{1cm} (104)
6.5.2 Worst-case Power Constraint (WPC)

Alternatively, we may take a single constraint from an equivalent BS $k_i$ having for each symbol stream the precoding weights whose norm is maximum among all BSs [33]:

$$P_{\text{max}} \geq \sum_{i=1}^{N} \sum_{l=1}^{R} \sum_{j=1}^{m_i} p_{ij}^l \Omega_{ij}$$

$$\Omega_{ij}^l = \max_{k=1,...,8} \left( \hat{w}_{ij}^k H \hat{w}_{ij}^k \right)$$

where $\hat{w}_{ij}^k$ is the $l$-th column of $\hat{W}_{ij}^k$ defined in (80), when also maximizing the weighted sum rate [26]:

$$f \left( P_1, ..., P_R \right) = \sum_{i=1}^{R} \log \left( 1 + \frac{1}{N} \sum_{l=1}^{R} \sum_{j=1}^{m_i} \log \left( 1 + p_{ij}^l \left( \lambda_{ij}^l \right)^2 \right) \right)$$

In the same way that in previous sub-optimal solution (102), the conventional waterfiling solution for the single power constraint in (105) is given by:

$$p_{ij}^l = \left( K \frac{\mu_{ij}}{\Omega_{ij}^l} - \frac{1}{\left( \lambda_{ij}^l \right)^2} \right)^*$$

where $K$ has been found by equating the worst power constraint in (105). Now, it is not necessary to scale the powers as the per-BS power constraints will be satisfied, and the rate achieved by the $i$-th RS is:

$$\tilde{r}_i = \frac{1}{N} \sum_{l=1}^{R} \sum_{j=1}^{m_i} \log \left( 1 + p_{ij}^l \left( \lambda_{ij}^l \right)^2 \right)$$

In order to upper limit the transmission rate on the first hop according to the modulation constraint in (69), also formulated as: $\log \left( 1 + p_{ij}^l \left( \lambda_{ij}^l \right)^2 \right) \leq S_{\text{max}}$ (79), we have to do it in the waterfiling optimization. Therefore, the solution for the power allocated would be:

$$p_{ij}^l = \left( \frac{P_{\text{max}} + \sum_{i=1}^{N} \sum_{l=1}^{R} \sum_{j=1}^{m_i} \Omega_{ij}^l \left( \lambda_{ij}^l \right)^2}{m_i \sum_{i=1}^{R} \mu_i} \frac{\mu_i}{\Omega_{ij}^l} - \frac{1}{\left( \lambda_{ij}^l \right)^2} \right)^*$$

where $P_{\text{max}}$ is the maximum power that can be allocated to each transmission mode of each RS so as not to exceed the maximum spectral efficiency $S_{\text{max}}$ of the LTE-A MCS (see details in 5.4.2):

$$P_{\text{max}} = \left( 2^{S_{\text{max}}} - 1 \right) \left( \lambda_{ij}^l \right)^2$$

This upper limit can be also applied to the sub-optimal solution (SPC) in (102).

6.5.3 Transmission time allocation

Using any of the two solutions in sections 6.5.1 and 6.5.2 (SPC or WPC), the $R+1$ transmission times for the first and second hop are obtained by solving a full-rank linear system of equations built from the following linear constraints:

$$\alpha_1 + \sum_{q=1}^{R} \alpha_{2q} = 1$$

$$\alpha_1 \tilde{r}_i - \alpha_{2q} \tilde{r}_{2q} = 0 \quad i = 1, ..., R$$

where

$$\tilde{r}_i = \frac{1}{N} \sum_{l=1}^{R} \sum_{j=1}^{m_i} \log \left( 1 + p_{ij}^l \left( \lambda_{ij}^l \right)^2 \right)$$
It can easily be verified that the values for $\alpha$ are positive numbers between 0 and 1, as the first equation force at least one $\alpha$ different from 0 and, consequently, the second group of equations force all $\alpha$ different from 0, while its values are limited to be lower than 1.

It can also be observed that the solution for the transmission time allocation is unique, as the system of equations in (111) is a determined compatible system (i.e. it has the same number of unknowns than equations).

Explicitly, the solution for the transmissions times (for $F=R$) is:

$$
\begin{bmatrix}
\alpha_1 \\
\alpha_{21} \\
\alpha_{22} \\
\vdots \\
\alpha_{2R}
\end{bmatrix} = \begin{bmatrix}
1 & 1 & 1 & \cdots & 1 \\
\tilde{r}_1 & -r_{211} & 0 & \cdots & 0 \\
\tilde{r}_2 & 0 & -r_{222} & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\tilde{r}_R & 0 & 0 & \cdots & -r_{2RR}
\end{bmatrix}^{-1} \begin{bmatrix}
1 \\
0 \\
0 \\
\vdots \\
0
\end{bmatrix}
$$

6.5.4 Simulation results

The evaluation of the proposed approach is done on a radio access network based on LTE-A specifications [5]. A hexagonal deployment is considered (see section 4.1) and an outdoor homogeneous scenario is deployed (see section 4.2.1), following the simulation parameters detailed in section 4.2.4. $B=3$ BSs and a total of $R=6$ RSs are deployed on the macrocell. On each scenario, $M=6$ users are dropped uniformly in the macrocell arrangement, one assigned to each RS. All the RSs are at the same distance $d$ to their associated BS, equal to 60% of the cell radius. The number of antennas is $n_B^R=4$ at the BS, $n_R^p=2$ at the RS and $n_M^f=1$ at the UE. Inter site distances are 1000, 1500, 2000, 2500 and 3000 m. Overheads at the system level are considered from Table 7: $\eta_B^w=0.67$ for the BS-RS link and $\eta_B^w=0.71$ for the RS-UE link.

In the following study, the optimal solution proposed in (98) (‘relayed CoMP-JP’ in legend) is compared to the SPC and WPC approaches in section 6.5.1 and 6.5.2. Optimal and suboptimal approaches are evaluated for TDMA in the second hop, that is: $F=R$. In order to avoid unfair service to deprived users, they are evaluated under weighted sum rate (‘WSR’ in legend), and the weights are inversely proportional to the rates in the second hop, that is $\mu_i=1/r_{2iq}$.

Figure 31 displays cell-edge spectral efficiency vs. cellular spectral efficiency (see computation details in Annex D) in Topology A (without inter-macrocell interference), when applying and not modulation constraints (‘MCS 64QAM 4/5’ in figure). When applying modulation constraints, the limitation specified in (69) for 64-QAM and 4/5 code rate is applied over each transmission mode, following the expression in (109) for the suboptimal solutions.

Figure 32 displays cell-edge spectral efficiency vs. cellular spectral efficiency in Topology B (with inter-macrocell interference), when applying and not modulation constraints (‘MCS 64QAM 4/5’ in figure).

When comparing the optimal solution and the suboptimal ones, observed losses in both in $S_e$ and $r_{out}$ are negligible. When the modulation constraints are imposed, the suboptimal solutions are also very good approaches; the observed losses in both $S_e$ and $r_{out}$ are also negligible due to the inclusion of the maximum transmission rate that can be achieved in the waterfilling algorithm.

When inter-macrocell interference is taken into account (Topology B), the suboptimal solutions slightly differ from the optimal one, and it seems that SPC is a better approach than WPC, as it takes into account the precoding matrixes of all the BSs, while the suboptimal solution only consider the precoding matrixes of the worst BSs.

In addition, it can be observed that higher order modulation and coding schemes are needed for low ISD, since the difference is higher between the results without and with MCS (‘MCS 64QAM 4/5’ in figures) for low ISD than for high ISD.
Figure 31: Cell-edge spectral efficiency vs. cellular spectral efficiency for relay-assisted CoMP-JP using optimal and suboptimal resource allocation and F=6, when applying and not modulation constraints in Topology A. ISD are 1000m(black), 1500m(blue), 2000m(red), 2500m(magenta) and 3000m(green).

Figure 32: Cell-edge spectral efficiency vs. cellular spectral efficiency for relay-assisted CoMP-JP using optimal and suboptimal resource allocation and F=6, when applying and not modulation constraints in Topology B. ISD are 1000m(black), 1500m(blue), 2000m(red), 2500m(magenta) and 3000m(green).
6.6 Resource allocation for fixed duration of the phases

In section 6.4, it was observed that the joint optimization of coordinated BS-RS links (through CoMP-JP) and duration of the relay-receive and relay-transmit phases brings large benefits. This approach is however not convenient when considering multiple coordinated cells: if each macrocell adapts the duration of the transmission independently, the inter-macrocell interference power observed in each transmission slot may be time-varying, a harsh and undesirably situation for the cellular system.

For that reason, this chapter is focused on formulate the problem when the duration of the relay-receive and relay-transmit phases are fixed beforehand, and then inter-macrocell interference is stationary during the transmission time interval.

In section 6.6.1 we review how the system performance varies with the duration of the relay-receive and relay-transmit phases, to finally fix the best value to those durations following the transmission frames durations of the LTE-A. In section 6.6.2 the problem is set, and a simple and efficient algorithm to allocate power on the BS-RS link is proposed and developed. Section 6.6.3 present the simulation results; the system performance is compared to the case were the duration of the phases was variable, to observe the differences.

6.6.1 Fixed time distribution

The duration of time slot \( \alpha \) are based on the results obtained when it is optimized. The optimum \( \alpha \) in terms of spectral efficiency is a random variable that depends on the particular scenario and the target function to be maximized, but it is intuitive to think that less time will be designated to the relay-receive phase as the achieved rate in the BS-RS link is higher than the achieved rate in the RS-UE link due to the benefits of CoMP-JP.

Through the simulation results, it was observed that \( \alpha \) mean value is lower for \( F=6 \) than for \( F=1 \). Fixing the position of the RS at 60% of the cell radius, the mean value of the optimum \( \alpha \) does not exhibit a significant variation with higher inter site distances for \( F=6 \) (no interference in the RS-UE link). For \( F=1 \) it increases as ISD increases due to the fact that interference in the second hop is reduced with higher ISD while rate losses in the BS-RS link are larger due to increased distance.

However, the main variation of \( \alpha \) values is given by the objective function to be maximized, as it was observed in Figure 28. When using WSR, lower values of \( \alpha \) were observed than for SR, as WSR is more concerned about users having bad quality channels in the RS-UE link.

As it was demonstrated in section 6.4.1, the best access mode for the second hop is \( F=1 \). So, from now on, we’ll only consider this case. Therefore, we have to fix the value of \( \alpha \) for the first hop (BS-RS link) and the value for the duration of the second hop (RS-UE link) can be directly computed as: \( \alpha_2=1-\alpha_1 \).

For the following studies we will fix the relay-receive and relay-transmit phases to the values in the following tables. The mean value obtained in the optimization when \( \alpha \) was optimized is taken from Figure 28 (‘mean value’ in tables). Afterwards, it is fixed to a duration of the LTE-A transmission frames (‘LTE-A frame duration’ in tables). In LTE-A there are different configuration of the subframes durations; there are 9 subframes which have to be distributed between uplink (UL) and downlink (DL) transmissions. For that reason, taking into account that one subframe is allocated for the UL and 8 subframes for the DL, we have to distribute the 8 subframes for the 1st hop and 2nd hop transmission in the best way. The values selected are displayed in Table 9 when no modulation constraint is imposed, and in Table 10 when LTE-A modulation constraints are imposed.

See Annex F for further details of the LTE-A frame configuration.
Access modes based on CoMP for relay transmissions in 4G systems

Table 9: Duration of the relay-receive phase

<table>
<thead>
<tr>
<th>Topology</th>
<th>$\alpha_1$ mean value</th>
<th>LTE-A frame duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - SR</td>
<td>0.14</td>
<td>1/8</td>
</tr>
<tr>
<td>A - WSR</td>
<td>0.20</td>
<td>2/8</td>
</tr>
<tr>
<td>B - SR</td>
<td>0.21</td>
<td>2/8</td>
</tr>
<tr>
<td>B - WSR</td>
<td>0.37</td>
<td>3/8</td>
</tr>
</tbody>
</table>

Table 10: Duration for the relay-receive phase for 64QAM 4/5

<table>
<thead>
<tr>
<th>Topology</th>
<th>$\alpha_1$ mean value</th>
<th>LTE-A frame duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - SR</td>
<td>0.25</td>
<td>2/8</td>
</tr>
<tr>
<td>A - WSR</td>
<td>0.32</td>
<td>3/8</td>
</tr>
<tr>
<td>B - SR</td>
<td>0.26</td>
<td>2/8</td>
</tr>
<tr>
<td>B - WSR</td>
<td>0.37</td>
<td>3/8</td>
</tr>
</tbody>
</table>

6.6.2 WSR-based resource allocation

Following the problem in section 6.4, we want to allocate the resources based on the maximization of the weighted sum-rate (WSR) criterion that allows adding certain QoS over the served users depending on priorities $\mu_i$:

\[
\begin{align*}
\text{maximize} & \quad -\sum_{i=1}^{R} \mu_i r_i \\
\text{s.t.} & \quad \left\{ \begin{array}{l}
\frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{m_i} \log_2 \left( 1 + \frac{p_j^i}{\delta_{ij}^R} \right) - \alpha_1 \leq 0 \quad i = 1, \ldots, R \\
r_i - \alpha_2 r_{i2} \leq 0 \\
\sum_{i=1}^{N} \sum_{i=1}^{R} \sum_{j=1}^{m_i} p_j^i \delta_{ij}^R - p_{\max}^k \leq 0 \\
p_j^i \left( 2^{\delta_{\max}^i} - 1 \right) \left( \lambda_{ij}^i \right)^{-2} \leq 0 \\
r_i \leq 0 \\
p_j^i \leq 0
\end{array} \right. \\
\text{and} & \quad \mu_i \geq 0 \\
\end{align*}
\]

\[ (P_{\text{WSR}}) \] (112)

where $\alpha_1$ and $\alpha_2$ are fixed, $\delta_{ij}^R$ is defined in equation (80) for the CoMP-JP case (for CoMP-CS/CB it is equal to 1) and $S_{\text{max}}^i$ is the maximum spectral efficiency for the LTE-A MCS. The user’s transmission rate is given by the minimum between the rate in the first and second hop, which is expressed in (112) with the first and second constraint. The expression for the transmission rate in the first hop would be slightly different in the CoMP-CS/CB (see section 6.2.2). Moreover, we have the per-BS power constraint, the modulation constraints and the rates and the powers have to be positive.

Note that problem (P_{\text{WSR}}) is convex and can be solved using standard convex optimization techniques, like interior point methods [32]. Nevertheless, we can further elaborate towards an efficient numerical algorithm based on the dual update methods [32][34] that will define a polynomial complexity algorithm along with a reduction of the number of variables to be optimized.

The main difficulty in solving (P_{\text{WSR}}) is caused by the max-rate constraints imposed by the transmissions in the second hop (second constraint in equation (112)). When they are active, the unique maximum WSR can be reached by many power allocation strategies. For example, all the
available power at the BSs could be used while adopting a transmission rate lower than the Shannon rate bound. It would be one solution but not the optimal one since power would therefore be wasted. In other words, we would like to optimize the power in the first hop in order not to depreciate it.

We deal with that drawback by transforming the max-rate constraints into power constraints per stream and reformulating the optimization problem (P_{WSR}).

Let us express the Lagrangian function of (P_{WSR}) in equation (112) as:

$$
L\left(\{r_i\}, \{p_{ij}^r\}, \{p_{ij}^l\}, \{\varphi_k\}, \{\psi_i\}, \{\eta_i\}, \{\phi_i^l\}, \{\phi_i^r\}\right) = -\sum_{i=1}^{R} \mu_i r_i + \sum_{i=1}^{R} \psi_i (r_i - \alpha_2 r_{z_i}) + \sum_{i=1}^{R} \varphi_k \left(\sum_{l=1}^{L} \sum_{j=1}^{M_l} \log_2 \left(1 + \left(\hat{\lambda}_{ij}^l \right)^2 \right) p_{ij}^l \right) - \sum_{i=1}^{R} \eta_i r_i - \sum_{i=1}^{R} \sum_{l=1}^{L} \sum_{j=1}^{M_l} \phi_i^l p_{ij}^l
$$

(113)

where \(\varphi_k\), \(\psi_i\), \(\eta_i\), \(\phi_i^l\) denote the Lagrange multipliers or dual variables associated to the max-power per BS, Shannon bitrate bound, max-rate constraints, and modulation constraint respectively. Finally, \(\eta_i, \phi_i^r\) are the Lagrange multipliers needed for having positive values of transmission rate and allocated power at BSs.

The conditions to minimize the Lagrangian as a function of the transmission rate \(r_i\) and allocated power \(p_{ij}^r\) become:

$$
\begin{align*}
\frac{\partial L}{\partial r_i} &= 0 & \rightarrow -\mu_i + \psi_i + \gamma_i - \eta_i &= 0 \\
\frac{\partial L}{\partial p_{ij}^r} &= 0 & \rightarrow -\frac{\alpha_i \psi_i}{N \ln 2} + \frac{\left(\hat{\lambda}_{ij}^l \right)^2}{1 + \left(\hat{\lambda}_{ij}^l \right)^2} p_{ij}^l + \sum_{k=1}^{R} \phi_k \delta_{jk}^l + \phi_i^r - \phi_i^l &= 0
\end{align*}
$$

(114)

The previous conditions allow having an expression for \(p_{ij}^r\) but only if there is at least one BS using its max power or the power allocated to \(p_{ij}^r\) is the maximum allowed (\(\varphi_k = 0\) or \(\phi_i^r = 0\)). However, if the second hop is limiting the maximum rate, not all the available power is needed (\(\varphi_k = 0\) \(\forall k\)). In such a case, there are multiple power allocation strategies providing maximum weighted sum-rate.

Since we are interested in attaining the maximum rate but using the minimum required power, we would like to transform the transmission rate inequalities in the second hop into max-power constraints in the first hop. In this regard, let us define the maximum power used in the first hop for the \(i\)-th RS as the solution of the optimization problem:

$$
\begin{align*}
\text{minimize} & \quad \frac{1}{\mu_i} \sum_{l=1}^{L} \sum_{j=1}^{M_l} p_{ij}^l \\
\text{s.t.} & \quad \alpha_2 r_{z_i} - \alpha_1 \sum_{l=1}^{L} \sum_{j=1}^{M_l} \log_2 \left(1 + \left(\hat{\lambda}_{ij}^l \right)^2 \right) p_{ij}^l \leq 0 \\
& \quad -p_{ij}^l \leq 0 \quad j = 1, \ldots, m_i
\end{align*}
$$

(115)

Problem (P_{WP}) consists of minimizing the power allocated on the first hop so as not to exceed the rate on the second hop.

The problem (P_{WP}) is convex and the power allocation turns out to be:

$$
p_{ij}^r (o_i) = \left[ \frac{\alpha_i \mu_i}{N \ln 2} - \frac{1}{\left(\hat{\lambda}_{ij}^l \right)^2} \right]^{+}, \quad o_i^* = 2 \left( \frac{1}{m_i} \sum_{l=1}^{L} \sum_{j=1}^{M_l} \left( \frac{a_{ij} \mu_i (\hat{\lambda}_{ij}^l)^2}{N \ln 2} \right) \right)
$$

(116)
This way we can define the maximum power that can be allocated the $i$-th RS so as not to waste power on the first hop. In other words, the total power employed for the transmission to the $i$-th RS is defined as:

$$P_{2i} = \sum_{j=1}^{N} \sum_{l=1}^{m} p_{ij}^l (\omega_l^*)$$ (117)

Note that solution in (116) for $(P_{\text{sp}})$ would be the optimal solution to the initial problem $(P_{\text{WSR}})$ if we had not the per-BS power constraint. But, as the power available at the BSs is limited, we have to include the definition of the maximum power that can be allocated in the first hop $P_{2m}$ in the whole problem $(P_{\text{WSR}})$.

Now, we reformulate the problem $(P_{\text{WSR}})$ in (112) taking into account the max-power per stream when we are limited by the transmission rate of the second hop (117):

$$\begin{align*}
\text{minimize} & \quad -\sum_{i=1}^{R} \mu_i r_i \quad \{ i = 1, \ldots, R \}, \{ k = 1, \ldots, B \} \\
& \begin{cases}
(\psi_i): \quad r_i - \alpha_i \frac{1}{N} \sum_{l=1}^{m} \log_2 \left(1 + \left(\lambda_{ij}^l\right)^2 p_{ij}^l\right) \leq 0 \\
(\phi_i): \quad \sum_{j=1}^{N} p_{ij}^l - P_{2i} \leq 0 \\
(\bar{\lambda}_{ij}): \quad \sum_{l=1}^{m} \sum_{j=1}^{p_{ij}^l} |\delta_{ij}^l| - P_{\max}^k \leq 0 \\
(\phi_j): \quad p_{ij}^l - (2^{\max} - 1)\left(\lambda_{ij}^l\right)^2 \leq 0 \\
(\eta_i): \quad -r_i \leq 0 \\
(\phi_o): \quad -p_{ij}^l \leq 0 \quad j = 1, \ldots, m_j \quad l = 1, \ldots, N
\end{cases}
\end{align*}$$ (118)

Notice that we have substituted the rate constraint in the second hop for the equivalent power constraint in the first hop, and we have included the Lagrange multipliers $\phi_i$ instead of $\gamma_i$ in (113) with the proper power constraint (in terms of $P_{\text{sp}}$) as obtained from (117). With this transformation, the problem $(\tilde{P}_{\text{WSR}})$ remains convex and we can find the power allocation easily.

The Lagrangian function of $(\tilde{P}_{\text{WSR}})$ is:

$$L\{r_1, \ldots, r_N, \phi_1, \ldots, \phi_R, \phi_1, \ldots, \phi_R, \eta_1, \ldots, \eta_N\} = -\sum_{i=1}^{R} \mu_i r_i + \sum_{i=1}^{R} \phi_i \left(\sum_{j=1}^{N} \sum_{l=1}^{m} p_{ij}^l - P_{2i}\right)$$
$$+ \sum_{i=1}^{R} \psi_i \left(r_i - \alpha_i \frac{1}{N} \sum_{l=1}^{m} \log_2 \left(1 + \left(\lambda_{ij}^l\right)^2 p_{ij}^l\right)\right) + \sum_{k=1}^{B} \phi_k \left(\sum_{l=1}^{m} \sum_{j=1}^{p_{ij}^l} |\delta_{ij}^l| - P_{\max}^k\right)$$
$$+ \sum_{i=1}^{R} \sum_{j=1}^{N} \sum_{l=1}^{m} \phi_j p_{ij}^l - (2^{\max} - 1)\left(\lambda_{ij}^l\right)^2 - \sum_{i=1}^{R} \eta_i r_i - \sum_{l=1}^{m} \sum_{j=1}^{p_{ij}^l} \phi_o p_{ij}^l$$ (119)

Hence, the conditions to optimize (118) become,

$$\begin{align*}
\frac{\partial L}{\partial r_i} &= 0 \quad \Rightarrow \quad -\mu_i + \psi_i - \eta_i = 0 \\
\frac{\partial L}{\partial p_{ij}^l} &= 0 \quad \Rightarrow \quad -\frac{\alpha_i \psi_i}{N \ln 2} \left(\lambda_{ij}^l\right)^2 + \sum_{k=1}^{B} \phi_k |\delta_{ij}^l| + \phi_i + \phi_j - \phi_o = 0
\end{align*}$$ (120)

From which we can easily obtain the power allocation:
\[
\psi_i = \mu_i, \quad \eta_i = 0, \quad \varphi_i = 0, \quad \phi_i = 0
\]

\[
p_{ij}^l(\varphi_k, \varphi_l) = \left[ \frac{\alpha_i}{N \ln 2} \sum_{k=1}^{B} \varphi_{ik}^{\delta_{ik}} + \varphi_l \right] - \frac{1}{2^{2\max -1}} (\lambda_i^{jl})^2
\]

(121)

The power allocation depends on the lagrange multipliers associated to the per-BS power constraints \( \varphi_i \) and the per-user power constraint \( \varphi_l \). In order to update them properly, let us define the dual function of \( P_{\text{wSR}} \).

The dual function of \( P_{\text{wSR}} \) taking into account its Lagrangian and the solution in (121) is:

\[
g\left(\{\varphi_i\}, \{\bar{\varphi}_l\}\right) = -\sum_{i=1}^{R} \alpha_i \sum_{j=1}^{m} \log_2 \left(1 + \left(\lambda_i^{jl}\right)^2 p_{ij}^l\right) + \sum_{k=1}^{B} \varphi_k \left(\sum_{j=1}^{m} \sum_{i=1}^{N} p_{ij}^l \delta_{ik} - P_{\text{max}}^k\right) + \sum_{l=1}^{N} \bar{\varphi}_l \left(\sum_{j=1}^{m} p_{ij}^l - P_{2l}\right)
\]

(122)

The optimal values of the Lagrange multipliers are obtained by maximizing the dual function,

\[
(P_{\text{DF}}): \quad \text{maximize} \quad g\left(\{\varphi_i\}, \{\bar{\varphi}_l\}\right) \\
\quad \text{s.t.} \quad \varphi_i \geq 0 \quad \forall k, \quad \bar{\varphi}_l \geq 0 \quad \forall i
\]

(123)

Since \( P_{DF} \) is convex, gradient-type search is guaranteed to converge to the global optimum of (123). Search directions given in (122) by

\[
d_k = \sum_{j=1}^{m} \sum_{i=1}^{N} p_{ij}^l \delta_{ik} - P_{\text{max}}^k, \quad \tilde{d}_i = \sum_{i=1}^{N} p_{ij}^l - P_{2i}
\]

(124)

coincide with the subgradient, [34]. This suggests that if a given constraint is exceeded the associated Lagrange multiplier should be increased, or decreased otherwise.

The second subgradient in (124) indicates if we are using more power than the necessary to achieve the rate on the second hop (since \( P_{\text{wSR}} \) describes the maximum power that can be allocated on the first hop in order not to exceed the rate on the second hop). Therefore, it can be replaced by next subgradient, which also accounts for the maximum rate:

\[
\tilde{d}_i = \alpha_i \frac{1}{N} \sum_{j=1}^{m} \sum_{i=1}^{N} \log_2 \left(1 + \left(\lambda_i^{jl}\right)^2 p_{ij}^l\right) - \alpha_i r_{2i}
\]

(125)

In this respect, we can avoid calculating \( P_{2i} \) in (117) given by the minimization problem \( P_{\text{SPR}} \).

Finally, the transmission rate and power allocation thus obtained become,

\[
p_{ij}^l(\varphi_k^*, \bar{\varphi}_l^*) = \left[ \frac{\alpha_i}{N \ln 2} \sum_{k=1}^{B} \varphi_{ik}^{\delta_{ik}} + \bar{\varphi}_l \right] - \frac{1}{2^{2\max -1}} (\lambda_i^{jl})^2
\]

(126)

The subgradients required to update the Lagrange multipliers are:

\[
d_k = \sum_{i=1}^{N} \sum_{j=1}^{m} p_{ij}^l \delta_{ik} - P_{\text{max}}^k, \quad \tilde{d}_i = \alpha_i \frac{1}{N} \sum_{j=1}^{m} \sum_{i=1}^{N} \log_2 \left(1 + \left(\lambda_i^{jl}\right)^2 p_{ij}^l(\varphi_k^*, \bar{\varphi}_l^*)\right) - \alpha_i r_{2i}
\]

(127)
Note that the power allocation in (126) has a significantly reduced complexity: the number of variables to be optimized is independent on the number of transmission modes. In other words, the variables to optimize \( \phi_k \) and \( \phi_i \) are independent of the sub-index \( j \), which accounts for the spatial transmission mode, and of the super-index \( l \), which refers to the subcarrier frequency. This makes the problem easier to multicarrier systems (OFDM, OFDMA systems), where the number of transmission modes scales linearly with the number of subcarriers.

The algorithm presented in Table 11 compiles the method, and it is able to provide the optimal values for \( \phi_k \) and \( \phi_i \) with a polynomial complexity. It updates \( \phi_i \) following the ellipsoid method, for each step of the bisection method over \( \phi_k \), until all the \( \phi_k \) converge to the optimal values and hence the optimal solution is achieved.

**Table 11: Algorithm solving \( P_{\text{WSR}} \) for \( B=3 \) and \( R=6 \)**

| Initialize: \( \phi_1^{\text{max}}, \phi_1^{\text{min}}, \phi_2^{\text{max}}, \phi_2^{\text{min}}, \phi_3^{\text{max}}, \phi_3^{\text{min}} \) |
| while \( |\phi_1^{\text{max}} - \phi_1^{\text{min}}| \leq \varepsilon \) do |
| \( \phi_1 = \frac{1}{2} \left( \phi_1^{\text{max}} + \phi_1^{\text{min}} \right) \) |
| while \( |\phi_2^{\text{max}} - \phi_2^{\text{min}}| \leq \varepsilon \) do |
| \( \phi_2 = \frac{1}{2} \left( \phi_2^{\text{max}} + \phi_2^{\text{min}} \right) \) |
| while \( |\phi_3^{\text{max}} - \phi_3^{\text{min}}| \leq \varepsilon \) do |
| \( \phi_3 = \frac{1}{2} \left( \phi_3^{\text{max}} + \phi_3^{\text{min}} \right) \) |
| \( [\tilde{\phi}_1, ..., \tilde{\phi}_6] = \text{Ellipsoid method} \} \) |
| Initialize \( \tilde{\phi}_1, ..., \tilde{\phi}_6 \) |
| Repeat |
| - Compute \( p_i' \left( \varphi_i, \varphi_2, \varphi_3, \vartheta_i \right) \) given by (126) |
| - Compute subgradient \( \tilde{d}_i \) given by (127) |
| - Update \( \tilde{\phi}_1, ..., \tilde{\phi}_6 \) [28] |
| until convergence \} |
| if \( d_1 < 0 \), \( \varphi_1^{\text{max}} = \varphi_1 \), else \( \varphi_1^{\text{min}} = \varphi_1 \) |
| end while |
| if \( d_2 < 0 \), \( \varphi_2^{\text{max}} = \varphi_2 \), else \( \varphi_2^{\text{min}} = \varphi_2 \) |
| end while |
| if \( d_3 < 0 \), \( \varphi_3^{\text{max}} = \varphi_3 \), else \( \varphi_3^{\text{min}} = \varphi_3 \) |
| end while |

The values of \( \varphi_k \), \( \varphi_i \) in algorithm in Table 11 are updated following the bisection method for \( \varphi_k \), and the ellipsoid method [34] for \( \tilde{\varphi}_i \). Those methods are selected because the power allocation in (126), for a given user \( i \) and transmission mode \( j \), depends on the lagrange multiplier associated to its \( i \)-th per-user power constraint \( \tilde{\varphi}_i \) and also depend on the lagrange multipliers associated to all the per-BS power constraints \( \varphi_k \), \( k = 1, ..., B \). I mean, \( \varphi_k \), \( k = 1, ..., B \) are involved on the power allocation of all the transmission modes, while \( \tilde{\varphi}_i \) is only involved in the power allocation of the \( i \)-th user. For that reason, ellipsoid method is selected to update \( \tilde{\varphi}_i \), and bisection method is selected to update each \( \varphi_k \), once done the power allocation on all the users.

The bisection method consist on update the lagrange multipliers repeatedly by bisecting an interval. At each step the method divides the interval into two subintervals by computing the midpoint of the interval, and on each step the subinterval where the solution lies is selected (according to the computation of the subgradient).
The ellipsoid method is an iterative method to update the lagrange multipliers by generating a sequence of ellipsoids whose volume uniformly decreases at every step [34]. Algorithm in Table 11 updates \( \bar{\phi}_i \) following the ellipsoid method, for each step of the bisection method over \( \varphi_k \), until all the \( \varphi_k \) converge to the optimal values. Then the optimal solution is achieved.

### 6.6.3 Simulation results

The evaluation of the proposed approach is done on a radio access network based on LTE-A specifications [5]. A hexagonal deployment is considered (see section 4.1) and an outdoor homogeneous scenario is deployed (see section 4.2.1), following the simulation parameters detailed in section 4.2.4. \( B=3 \) BSs and a total of \( R=6 \) RSs are deployed on the macrocell. On each scenario, \( M=6 \) users are dropped uniformly in the macrocell arrangement, one assigned to each RS. The number of antennas is \( n_B=4 \) at the BS, \( n_R=2 \) at the RS and \( n_M=1 \) at the UE. Inter site distances are 1000, 1500, 2000, 2500 and 3000 m. Overheads at the system level are considered from Table 7: \( \eta_{BW}=0.67 \) for the BS-RS link and \( \eta_{BW}=0.71 \) for the RS-UE link.

In the following study, the optimal solution proposed in equation (126) for fixed duration of the relay-receive and relay-transmit phases is evaluated for the sum rate (SR) and the weighted sum rate (WSR) in \( f(.) \), over 1000 random user deployments for \( F=1 \) in the second hop (‘Relayed CoMP-JP fixed duration’ in legends). When maximizing the WSR, the weights are inversely proportional to the rate on the second hop in order to avoid unfair services to deprived users (i.e. \( \mu_i = 1/r_{iq} \)).

The optimal solution for fixed durations of the relay-receive and relay-transmit phases is compared to the optimal solution for variable durations of the phases (‘Relayed CoMP-JP’ in legends), which was developed in section 6.4 (specifically, in equation (98)) and results are taken from section 6.4.1.

The relayed CoMP-JP strategies -with fixed or variable durations of the phases- are compared with a relay-assisted transmission with uncoordinated BSs when the duration of the relay-receive and relay-transmit phases is also fixed beforehand (‘Relayed BF-TDMA fixed duration’ in legend). In this later case, the sum rate is adopted and each BS serves its associated RS under round-robin TDMA.

Figure 33 displays cell-edge spectral efficiency vs. cellular spectral efficiency (see computation details in Annex D) in Topology A (without inter-macrocell interference) when applying modulation constraints (‘64QAM 4/5’ in legend) and not. Figure 34 displays cell-edge spectral efficiency vs. cellular spectral efficiency in Topology B (with inter-macrocell interference) when applying modulation constraints (‘64QAM 4/5’ in legend) and not.

Both figures show significant gains in terms of cellular spectral efficiency and cell-edge spectral efficiency by relayed CoMP-JP strategies as compared to relayed BF-TDMA. Moreover when \( \alpha \) is optimized, the gains in terms of spectral efficiency and cell-edge spectral efficiency are comparable with the fixed \( \alpha \) case (‘fixed duration’ in figures). This confirms the possibility of having systems gains even if the duration of phases is kept fixed over the time.

Notice that the last observation is very important: it facilitates the adoption of relay transmissions in next-generation wireless systems, as this guarantees the stationarity of other cell-clusters interference within transmission frames.
Access modes based on CoMP for relay transmissions in 4G systems

Figure 33: Cell-edge spectral efficiency rate vs. cellular spectral efficiency for relay-assisted transmissions with fixed duration of the phases, when applying (right) and not (left) modulation constraints in Topology A. ISD are 1000m(black), 1500m(blue), 2000m(red), 2500m(magenta) and 3000m(green).

Figure 34: Cell-edge spectral efficiency rate vs. cellular spectral efficiency for relay-assisted transmissions with fixed duration of the phases, when applying (right) and not (left) modulation constraints in Topology B. ISD are 1000m(black), 1500m(blue), 2000m(red), 2500m(magenta) and 3000m(green).
7 FEMTO-RELAYS TRADEOFF ANALYSIS

Relay-based deployments cannot compete with femtocells deployments due to the increased utilisation of radio resources arising from the half-duplexing of the RS and the for-free DSL bandwidth given to FAP (which implies an enhanced transmission rate in the FAP-based transmission than in a RS-assisted transmission). Moreover, these deployments are not comparable to serve indoor users owing to the poorer indoor penetration of the outdoor RS. However, relays-based deployments can complement FAP-based deployments to serve those users without a serving FAP and then improve the indoor coverage. Therefore, relay-based and femto-based networks can coexist in the same area and in the same spectrum, by scheduling both networks in different time instances. To that end, an advanced MIMO access scheme based on CoMP has been defined for relay transmissions (as the one evaluated in section 6).

In the practical deployment envisioned here, it is considered that all UEs with an associated FAP will be served by its FAP, while those UE without a FAP available or those out of the FAP coverage area will be served by the BS/RS.

Orthogonal subframes in TDD mode of LTE are assumed for RS transmissions and FAP transmission, so that the interference is minimized between them. The access mode is detailed in section 7.1, for the BS/RS-assisted network and the FAP-based network. The scheduler is described in section 7.2 and the simulator schematic in section 7.3. Section 7.4 provides the simulation results for the joint evaluation of FAP and RS-assisted networks when adopting different criterions for the transmission time allocation.

7.1 Access mode

For radio access to FAP and RS, we will assume TDMA: RS-assisted transmissions and FAP-based transmissions are orthogonal in time (see Figure 35). This way, interference can be considered as stationary.

![Figure 35: Access mode for joint FAP and BS/RS-based deployment.](image)

The fraction of time (or number of subframes) devoted to each network can be optimised following different criterions. For simulation results, α (i.e. the time devoted for the RS-assisted network) will be optimized following two different criterions: one to have a fixed relation between the spectral efficiencies per user of each network, and another to have a fixed relation between the transmission time allocated to each user. Moreover, we have to take into account the LTE-A subframe structure and also that the maximum delay for a voice transmission service is 20ms.

It is assumed that all FAPs can serve simultaneously its associated users with an effective interference management, while BS/RS serve the users with a round robin TDMA algorithm until serve all the users (see more details in section 7.2). Therefore, α is divided into orthogonal transmissions (BS-RSs and RSs-UEs, in Figure 35) where one user per RS can be served. On each sub-slot for BS-RSs and RSs-UEs transmission, the access mode detailed in section 7.1.1 for the relay-based transmission is used.

7.1.1 Access mode in the RS-assisted network

In-band wireless backhauling between BS and RS is assumed. RS are placed in a high position so there is LOS between BS and RS and high spectral efficiency can be expected. Time
division duplexing (TDD) mode is assumed between the first and the second hop. The fraction of time devoted to the BS-RS link can be optimised for maximum transmission rate according to the possible subframe distributions in the TDD mode.

On the first hop (BS-RS link) multiple base stations coordinate their MIMO transmissions in the BS-RS in-band for the downlink. Two different downlink transmission strategies based on Coordinated Multi-Point (CoMP) are considered:
- Joint Processing (CoMP-JP)
- Coordinated Scheduling/Beamforming (CoMP-CS/CB)

With CoMP-JP, signals designated for a single RS are simultaneously transmitted from multiple neighboring BS. These BS cooperate in order to work as a single transmitter with geographically separated transmit antennas. It is considered that BSs transmit simultaneously to multiple RS located in the macrocell, and hence improved system spectral efficiency can be achieved. When CoMP-JP is used in conjunction with the BD-ZF algorithm, it resolves the inter-cell interference created in the macrocell.

The resource allocation for relayed CoMP-JP is done as detailed in section 6.2.1 and 6.6.2 for fixed duration of the relay-receive and relay-transmit phases.

With CoMP-CS/CB, RS scheduling and beamforming are dynamically coordinated among neighboring BS in order to control and reduce the interference. One way to control the inter-cell interference is by orthogonalizing BS transmissions in time. Then, each BS can simultaneously serve the multiple in-cell RSs following a MU-MIMO technique based on BD-ZF.

The resource allocation for relayed CoMP-CS/CB is done as detailed in section 6.2.2 and 6.6.2 for fixed duration of the relay-receive and relay-transmit phases.

On the second hop (RS-UE link) each RS transmits to a single UE, and the different UE associated to each RS are served under round-robin TDMA. RS transmit simultaneously and hence they interfere each other. RS transmissions can also be orthogonalized in time, but it results in a reduction of the system spectral efficiency (see results in section 6.4.1).

When considering a multi-cell deployment, if each macrocell adapts the duration of the phases independently, the inter-macrocell interference observed would be time varying. For that reason, the duration of the phases is fixed beforehand, accordingly to the LTE-A transmission subframes duration, in order to have stationary interference on each link. The subframe pattern adopted is the best possible according to what was defined in [21] and [22].

7.1.2 Access mode in the FAP-based network

The access methods to FAPs are taken from section 3.5 of [8].

7.2 Scheduler

The scheduling is implemented independently for the RS-assisted transmission and the FAP-based transmission.

For RS scheduling, usually resource management is divided in two steps: user scheduling and radio resource allocation. In this respect, users to be served are scheduled under a round-robin policy, so that all UE in the macrocell are served. Once they have been selected, the radio resource allocation (transmitted power, beamformers) can be performed by prioritizing each selected UE, so that a certain QoS is provided. While we recognize that this strategy is not optimum, it simplifies greatly the problem. A reasonable criterion is that user’s priority is taken as the inverse of the capacity on the second hop (RS-UE link) so as to avoid unfair service to deprived users: \( \mu_i = 1/r_{2i} \). This way, in comparison with the sum-rate criterion (equal priorities to all users), a weighted sum-rate criterion would perform better in terms of cell-edge spectral efficiency while losing in terms of spectral efficiency. Even thought, those priorities are not suitable for FAP-based transmission and the comparison would not be fair. Other criteria, like
the geometric mean of the transmission rates could be adopted but it does not lead to analytical results.

For FAP scheduling, the scheduler implements a weight system ad hoc to set send-queues on the basis of their characteristics and of the service data unit currently present. The decisions on the queue are periodically updated and the queue with the highest score is granted a Resource Block (RB) for transmission in the current frame and thereafter weights are re-calculated for all queues up to filling it.

7.3 Simulator

The simulator elaborated for the femto-relays tradeoff analysis is a static simulator with a modular structure in which one static network and user’s deployment is input to calculate relevant system performance parameters, based on given radio interfaces and radio resource management. The simulator is able to generate system performance statistics based on a number of independent runs. A simplified flow graph is shown in Figure 36.

![Figure 36: Schematic representation of the simulator.](image-url)
7.4 Evaluation of joint FAP and RS-assisted networks

In the following study, an evaluation has been performed at system level in order to elucidate the benefits in terms of spectral efficiency and cell-edge spectral efficiency given by the joint evaluation of FAP-based and RS-assisted networks.

To this end, a hotspot corporate scenario is deployed and a macrocell deployment is considered (consisting of three sectors of different cells) with two FAP areas and two RS per cell. Users can be placed indoor or outdoor. Macrocell deployment is detailed in section 4.1 and all results are taken under Topology B (with inter-macrocell interference). User’s deployment in a hotspot scenario is described in section 4.2.2 and simulation parameters can be found in section 4.2.5 [8].

On each realization 75 UE in average are dropped in the macrocell. Since all these UEs are deployed in a corporate scenario, we assume that they have an associated FAP nearby. However, which ones are active and which ones are not is a parameter of our simulation. Clearly, those users without an active FAP have to be served by the macro BS, either by direct BS transmission or by relay-assisted transmission. Therefore, all the dropped UE are split in two populations; those that will be served by a FAP-based transmission and those that will be served by RS-assisted transmission/direct transmission.

Two different relay-assisted transmission strategies are evaluated: relayed CoMP-JP and relayed CoMP-CS/CB. Relayed CoMP-JP is relay-assisted transmission with cooperation of the BS for the BS-RS link. Meanwhile, relayed CoMP-CS/CB does not consider cooperation among BS and BS transmissions are orthogonal in time to reduce the inter-cell interference. Both strategies are detailed in section 6.2. In the non-relayed case (users served only by the BS), the UE are served by BS following a CoMP-JP technique, where the joint processing is applied over the UE on the macrocell, as it is described in section 5. Simulation results are evaluated when maximizing the sum rate (SR).

The FAP-based transmissions are evaluated when applying decentralized resource allocation algorithms analysed in [9] based on message exchange (pricing algorithm) or without any message exchange (no-pricing algorithm). The qualities of backhaul assumed are: ideal or a FTTB@ 100Mbps.

7.4.1 Cellular spectral efficiency vs. cell-edge spectral efficiency of individual access schemes

Table 12 show the cellular spectral efficiency and the cell-edge spectral efficiency (see computation details in Annex D) achieved when the number of UE served by the FAP increases (thus simulating an increasing FAP density), for different transmission strategies:

- Direct transmission (‘CoMP-JP’ in Table 12 and Table 13),
- Relayed transmission (‘Rel CoMP-JP’ and ‘Rel CoMP-CS/CB’ in Table 12 and Table 13) and
- FAP-based transmission (‘FAP no pricing’ and ‘FAP pricing’ in Table 12 and Table 13).

Cellular spectral efficiency (‘Cell average’ in tables) is computed as the sum rate of the UE in a cell area averaged over many deployments and it is expressed in terms of bits/s/Hz/cell. Cell-edge spectral efficiency is defined as the peak achievable rate of the $\varepsilon$-percentile worst users in the macrocell over many deployments and it is given in terms of bits/s/Hz. It is computed for the $\varepsilon \in \{5\%, 15\\}$. $\%$UE served by BS or RS’ indicates the % of deployed UEs that are served by a BS/RS-based transmission and $\%$UE served by FAP’ indicates the % of the deployed UE that are served by a FAP-based transmission. The total number of deployed UEs is maintained.
In RS-assisted transmissions, the cellular spectral efficiency keeps constant as the number of UE served by RS is increased, because each time a group of 6 UEs is served (there are 6 RS deployed in the macrocell), selecting the UE with a round-robin policy TDMA-based. However, the cell-edge spectral efficiency increases when the number of UE served by the RS decreases because the time allocated to each UE is higher. The same behaviour is observed in the BS transmissions based on CoMP-JP. It can be observed that relay-based transmission significantly increases the cell-edge spectral efficiency with respect to the direct transmission BS-UE (‘CoMP-JP’) since RS are nearer the UE and it allows combating shadowing and path loss effects. In [21] it is shown that this is achieved with a lower transmitted power as compared to direct transmissions.

When comparing the relay-assisted transmissions (‘Rel CoMP-JP’ and ‘Rel CoMP-CS’), CoMP-JP achieves a nearly doubled cellular spectral efficiency. CoMP-CS/CB suffers some loses in spectral efficiency owing to the time division associated to coordination, and achieves and improved cell-edge spectral efficiency of the 5% worst users because the duration of the relay-receive and relay-transmit phases is optimized on each transmission scheme to enhance the spectral efficiency (and they differ from CoMP-JP to CoMP-CS/CB).

Results obtained for the FAP-based transmission elucidate that the cellular spectral efficiency is almost the same for the decentralized pricing and no pricing algorithms [9]. However, the pricing-based algorithm improves significantly the cell edge spectral efficiency.

<table>
<thead>
<tr>
<th>% UE served by BS or RS</th>
<th>100%</th>
<th>90%</th>
<th>80%</th>
<th>70%</th>
<th>60%</th>
<th>50%</th>
<th>40%</th>
<th>30%</th>
<th>20%</th>
<th>10%</th>
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<tbody>
<tr>
<td>Rel CoMP-JP</td>
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<tr>
<td>Cell average</td>
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<tr>
<td>Cell edge 5%</td>
<td>0.019</td>
<td>0.022</td>
<td>0.028</td>
<td>0.027</td>
<td>0.032</td>
<td>0.044</td>
<td>0.046</td>
<td>0.065</td>
<td>0.081</td>
<td>0.151</td>
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<tr>
<td>Cell edge 15%</td>
<td>0.070</td>
<td>0.078</td>
<td>0.083</td>
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<tr>
<td>Cell average</td>
<td>3.18</td>
<td>3.18</td>
<td>3.18</td>
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<tr>
<td>Cell edge 5%</td>
<td>0.045</td>
<td>0.048</td>
<td>0.053</td>
<td>0.061</td>
<td>0.074</td>
<td>0.089</td>
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<td>0.208</td>
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<tr>
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<td>0.074</td>
<td>0.083</td>
<td>0.096</td>
<td>0.114</td>
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<td>0.253</td>
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<td>Cell edge 5%</td>
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<td>% UE served by FAP</td>
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<tr>
<td>Cell average</td>
<td>×</td>
<td>14.84</td>
<td>38.19</td>
<td>59.47</td>
<td>82.50</td>
<td>107.07</td>
<td>126.02</td>
<td>144.89</td>
<td>167.87</td>
<td>187.19</td>
<td>214.71</td>
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<tr>
<td>Cell average</td>
<td>×</td>
<td>14.65</td>
<td>37.66</td>
<td>58.53</td>
<td>81.29</td>
<td>105.49</td>
<td>124.15</td>
<td>142.88</td>
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<tr>
<td>Cell average</td>
<td>×</td>
<td>6.18</td>
<td>16.04</td>
<td>25.02</td>
<td>34.68</td>
<td>44.89</td>
<td>52.61</td>
<td>60.27</td>
<td>69.57</td>
<td>77.50</td>
<td>88.75</td>
</tr>
<tr>
<td>FAP pricing</td>
<td></td>
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<tr>
<td>(100Mb/s</td>
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<td>backhaul)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell average</td>
<td>×</td>
<td>6.18</td>
<td>16.04</td>
<td>25.02</td>
<td>34.68</td>
<td>44.89</td>
<td>52.61</td>
<td>60.27</td>
<td>69.57</td>
<td>77.50</td>
<td>88.75</td>
</tr>
</tbody>
</table>

Table 12: Cellular spectral efficiency and cell-edge spectral efficiency (in bits/s/Hz) for FAP and RS network (assuming that only FAPs or only RS networks employ all the resources)
when the number of active FAPs is high under the ideal backhaul. For example, gains around 30% are observed when the percentage of users served by FAPs is around 70%-90%, and a maximum gain of 40% when all users are served by FAP. When the backhaul is non-ideal the performance of both types of decentralized algorithm tend to be the same, because in such a case FAPs are not employing all the power and the generated prices become zero [9].

Notice that the cell average spectral efficiency is degraded with respect the ideal backhaul case. An explanation for this behaviour is shown in Figure 37 that represents the cellular spectral efficiency in the FAP-based network as a function of the number of FUE (results are taken from Table 12, without pricing), for the two cases in the quality of the backhaul: ideal or a FTTB@100Mbps. It can be observed that, with an ideal backhaul the slope of the graph is higher (8.9 bits/s/Hz per user attached to a FAP) than for the non-ideal backhaul (3.6 bits/s/Hz per user). The backhaul quality depends on the serving FAP position in the building (it decreases with higher floors). This also explains why the cell-edge spectral efficiency achieved in non-ideal conditions is reduced as well, because the cell-edge spectral efficiency in ideal backhaul quality conditions is higher than the average spectral efficiency per user in non-ideal backhaul link (3.6bits/s/Hz/user).

![Figure 37: Cellular spectral efficiency vs. FAP density in FAP-based network.](image)

#### 7.4.2 Adoption of more efficient MCS

Since the BS-RS and RS-UE links are improved due to the proximity between the transmitter and the receiver, the performance of relay transmission schemes might be improved if a higher order constellation were adopted.

Table 13 show the cellular spectral efficiency and the cell-edge spectral efficiency achieved when the number of UE served by the FAP increases (for Direct transmission and Relayed transmissions), when higher modulation and coding schemes (MCSs) are used. In LTE-A, the maximum MCS is 64QAM, in table results are also taken when 256QAM is used in the first hop (‘256QAM 1st hop’) and when 256QAM can be used in both hops of the relay-assisted transmission (‘256QAM’).
**Table 13: Cellular spectral efficiency and cell-edge spectral efficiency (in bits/s/Hz) for RS network with higher MCS**

It can be observed that, when using higher modulation and coding schemes, the results in the relay-assisted transmissions are improved around 13% (when using 256QAM on both hops) as on each link more power can be allocated. Meanwhile, the direct transmission is only improved around 4% when using 256QAM, as BS are transmitting at their maximum allocated power.

The cell-edge spectral efficiency is approximately maintained for higher modulation and coding schemes, because when higher MCS are used the users benefited are those with good channel propagation conditions (where the system can allocate more power and it results in an increasing transmission rate) and the users with bad channel propagation conditions do not achieve a higher transmission rate.

In conclusion, results show the suitable application of CoMP-JP for relay-based transmissions, since benefits from both can be obtained in terms of spectral efficiency and cell-edge spectral efficiency. Therefore, with an effective transmission time allocation, RS can complement FAP-based deployments.
7.4.3 Transmission time allocation for joint FAP and RS-based deployments

In the following study, the time devoted to the FAP-based transmission and the RS-assisted transmission will be settled according to two different criteria:

- **Criterion 1**: to satisfy a fixed relation between the spectral efficiencies per user of the FAP-based network and RS-based network.

- **Criterion 2**: to satisfy a fixed relation between the transmission time allocation to the users in each network.

On one side, following criterion 1, the transmission time allocation is optimized to have a relation between the spectral efficiencies per user of both networks. Such relation depends on a design parameter \( k_1 \) allowing the operator one degree of flexibility to balance the resources towards relay users or FUEs \( (k_1=1 \) guarantees a homogeneous spectral efficiency per user):

\[
k_1 \alpha \frac{S_{\text{eff}, \text{BS/RS}}}{N_{u, \text{BS/RS}}} = \left(1 - \alpha\right) \frac{S_{\text{eff}, \text{FAP}}}{N_{u, \text{FAP}}}
\]

where \( S_{\text{eff}, \text{FAP}} \) and \( S_{\text{eff}, \text{BS/RS}} \) refer to the cellular spectral efficiency of a FAP-based transmission and a BS/RS-assisted transmission, respectively from Table 12; \( N_{u, \text{FAP}} \) and \( N_{u, \text{BS/RS}} \) are the number of users in the FAP-based network and the BS/RS-based network, respectively; \( \alpha \) is the time devoted for the BS/RS-based network, \((1-\alpha)\) is the time devoted for the FAP-based network; and \( k_1 \) is the network design parameter. Following criterion 1, the optimum value for the time allocation for the RS-based network is given by:

\[
\alpha_{\text{opt}, 1} = \frac{S_{\text{eff}, \text{FAP}}}{S_{\text{eff}, \text{FAP}} + k_1 \frac{N_{u, \text{FAP}}}{N_{u, \text{BS/RS}}} S_{\text{eff}, \text{BS/RS}}}
\]

This transmission time allocation allows for different cellular spectral efficiencies on each network: the cellular spectral efficiency on the FAP-based network is \( k_1 N_{u, \text{FAP}} / N_{u, \text{BS/RS}} \) times the cellular spectral efficiency on the RS-based network. So, once \( k_1 \) is fixed following the network operator’s decision, factor \( N_{u, \text{FAP}} / N_{u, \text{BS/RS}} \) is lower than 1 for low density FAP deployments (which benefits the users without a serving FAP) and it is higher than 1 for high density FAP deployments (thus benefitting the users attached to a FAP).

On the other side, criterion 2 only considers the number of users on each network and tries to make independent the transmission time allocation of the cellular spectral efficiencies on each network. It also depends on a design parameter \( k_2 \) to allow the operator one degree of flexibility to balance the resources towards relay users or FUEs \( (k_2=1 \) guarantees the same transmission time allocation per user, even they are served with a different transmission strategy depending if they are served by FAP or BS/RS):

\[
\alpha = \frac{k_2 (1 - \alpha)}{N_{u, \text{BS/RS}} / 6}
\]

It has been considered that the RS scheduling implements a round robin TDMA algorithm to serve on each slot 6 users (one per RS) and the FAP-based transmissions can simultaneously serve all the users attached to a FAP. Hence, the optimum transmission time allocation following criterion 2 is:

\[
\alpha_{\text{opt}, 2} = \frac{1}{1 + \frac{6}{k_2 N_{u, \text{BS/RS}}}}
\]
Criterion 2 is independent on the quality of the backhaul and on the transmission strategy used in the RS-based network (as it does not depend on the cellular spectral efficiencies of each network).

Moreover, in order to fix the duration of each phase, we have to consider the LTE-A frame structure and that the maximum delay for a voice transmission service is 20ms. In LTE-A the duration of a frame is 10ms and it can be split on 10 subframes, one of which is always allocated for synchronism. Therefore, the number of subframes is limited to 9 for data transmission. Moreover, the frame structure depends on the duplexing mode. In TDD the situation is worse, as the 9 subframes shall be also split between uplink (UL) and downlink (DL). See Annex F for further details of the LTE-A frame structure for different uplink-downlink configurations.

In mobile wireless data transmission, generally, more time is devoted to DL transmission than for the UL transmission. For that reason, we consider that 8 subframes can be allocated to DL and 1 for the UL. This way, from the 8 subframes devoted for the DL, we could assign subframes to:

- Direct transmission or Relayed transmission ($\alpha$)
- FAP-based transmission (1- $\alpha$)

In addition, we have to take into account that the maximum delay for a voice transmission is 20ms, and hence at least one subframe every two frames has to be allocated to each network. It means that the minimum value for $\alpha$ and 1- $\alpha$ is 1/16. Therefore, the value for $\alpha_{opt}$ has to be quantified into an integer number of LTE-A subframes over two LTE-A frames.

7.4.3.1 Transmission time allocation based on average spectral efficiency per user

Following the first criterion, the transmission time allocation is optimized to have a fixed relation between the average spectral efficiency per user of each network in terms of parameter $k_1$ (which indicates the “priority” given to the FUEs). Results are taken for $k_1=1$ (i.e. equal spectral efficiency per user) and $k_1=10$ (i.e. average spectral efficiency per user on the FAP-based network is 10 times higher than the average spectral efficiency per user on the BS/RS-based network).

The obtained transmission time devoted to RS-assisted transmissions ($\alpha$), once quantified, are presented in Table 14 and Table 15 for $k_1=1$ and for different transmissions strategies for BS/RS transmissions. Results for $k_1=10$ are presented in Table 16 and Table 17. This way, 1- $\alpha$ would be the time designated for the FAP-based transmission. The two cases for the backhaul are considered: an ideal backhaul and an FTTB@100Mbps backhaul link.

<table>
<thead>
<tr>
<th>% UE served by FAP</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ relayed CoMP-JP</td>
<td>1</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>14/16</td>
<td>12/16</td>
<td>0</td>
</tr>
<tr>
<td>$\alpha$ relayed CoMP-CS/CB</td>
<td>1</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>14/16</td>
<td>14/16</td>
</tr>
<tr>
<td>$\alpha$ CoMP-JP</td>
<td>1</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>13/16</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 14: Fraction of time devoted for RS network for an ideal backhaul link and $k_1=1$

<table>
<thead>
<tr>
<th>% UE served by FAP</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ relayed CoMP-JP</td>
<td>1</td>
<td>14/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>14/16</td>
<td>14/16</td>
<td>14/16</td>
<td>13/16</td>
<td>12/16</td>
<td>9/16</td>
</tr>
<tr>
<td>$\alpha$ relayed CoMP-CS/CB</td>
<td>1</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>14/16</td>
<td>14/16</td>
<td>12/16</td>
</tr>
<tr>
<td>$\alpha$ CoMP-JP</td>
<td>1</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>14/16</td>
<td>14/16</td>
<td>13/16</td>
</tr>
</tbody>
</table>

Table 15: Fraction of time devoted for RS network for FTTB@100Mbps backhaul link and $k_1=1$
Access modes based on CoMP for relay transmissions in 4G systems

<table>
<thead>
<tr>
<th>% UE served by FAP</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha) relayed CoMP-JP</td>
<td>11/16</td>
<td>11/16</td>
<td>11/16</td>
<td>11/16</td>
<td>10/16</td>
<td>9/16</td>
<td>8/16</td>
<td>7/16</td>
<td>4/16</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>(\alpha) relayed CoMP-CS/CB</td>
<td>13/16</td>
<td>13/16</td>
<td>13/16</td>
<td>13/16</td>
<td>13/16</td>
<td>13/16</td>
<td>12/16</td>
<td>12/16</td>
<td>11/16</td>
<td>9/16</td>
<td>6/16</td>
</tr>
<tr>
<td>(\alpha) CoMP-JP</td>
<td>12/16</td>
<td>13/16</td>
<td>13/16</td>
<td>12/16</td>
<td>12/16</td>
<td>11/16</td>
<td>10/16</td>
<td>8/16</td>
<td>6/16</td>
<td>4/16</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 16: Fraction of time devoted for RS network for an ideal backhaul link and \(k_1\)=10**

<table>
<thead>
<tr>
<th>% UE served by FAP</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha) relayed CoMP-JP</td>
<td>8/16</td>
<td>8/16</td>
<td>8/16</td>
<td>7/16</td>
<td>7/16</td>
<td>6/16</td>
<td>5/16</td>
<td>4/16</td>
<td>2/16</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>(\alpha) relayed CoMP-CS/CB</td>
<td>10/16</td>
<td>11/16</td>
<td>10/16</td>
<td>10/16</td>
<td>9/16</td>
<td>9/16</td>
<td>7/16</td>
<td>6/16</td>
<td>3/16</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>(\alpha) CoMP-JP</td>
<td>9/16</td>
<td>10/16</td>
<td>9/16</td>
<td>9/16</td>
<td>8/16</td>
<td>7/16</td>
<td>6/16</td>
<td>5/16</td>
<td>3/16</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

**Table 17: Fraction of time devoted for RS network for FTTB@100Mbps backhaul link and \(k_1\)=10**

It can be observed that when \(k_1\)=10 less time is devoted for the BS/RS-based network, and more time is given to the FAP-based network (which has a higher priority in terms of average spectral efficiency per user).

Moreover, the transmission time allocation also depends on the transmission strategy used in the BS/RS-based network; more time is devoted for the FAP-based transmissions in a deployment with FAPs and RS using CoMP-JP than the cases with RS using CoMP-CS/CB or without RS, because cellular spectral efficiency achieved with relayed CoMP-JP is higher.

7.4.3.2 Transmission time allocation for equal resource allocation

Following the second criterion, transmission time is optimized to have a fixed relation between the transmission time allocated to the users in each network.

This criterion is independent on the quality of the backhaul and on the transmission strategy used in the BS/RS-based network. Therefore, transmission time devoted to BS/RS-assisted transmissions (\(\alpha\)) is presented in next tables, once quantified over 2 LTE frames so as to satisfy the maximum delay for voice transmission (as it is detailed in section 7.4.3). Table 18 shows the transmission time allocation for \(k_2\)=1 (i.e. equal transmission time allocated to each user) and Table 19 for \(k_2\)=2 (i.e. double of time devoted for each user in the BS/RS-based network).

Notice that the transmission time allocated to the BS/RS-based network decreases with the % of users served by BS/RS and when \(k_2\)=2 more time is given for the BS/RS-based network.

<table>
<thead>
<tr>
<th>% UE served by FAP</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha) (rel CoMP-JP, rel CoMP-CS, CoMP-JP)</td>
<td>15/16</td>
<td>15/16</td>
<td>14/16</td>
<td>14/16</td>
<td>14/16</td>
<td>13/16</td>
<td>13/16</td>
<td>11/16</td>
<td>9/16</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

**Table 18: Fraction of time devoted for RS network for equal resource allocation for \(k_2\)=1**

<table>
<thead>
<tr>
<th>% UE served by FAP</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha) (rel CoMP-JP, rel CoMP-CS, CoMP-JP)</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>15/16</td>
<td>14/16</td>
<td>13/16</td>
<td>11/16</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

**Table 19: Fraction of time devoted for RS network for equal resource allocation for \(k_2\)=2**
7.4.4 Complementarity of relay transmissions in FAP deployments

Once established the transmission time allocation in section 7.4.3, the system cellular spectral efficiency can be computed as:

\[
S_{\text{eff,system}} = \alpha S_{\text{eff,BS/RS}} + (1-\alpha)S_{\text{eff,FAP}}
\]  

(132)

where \(\alpha\) refers to the transmission time devoted for the BS/RS transmission (taken from Table 14 and Table 15, Table 16 and Table 17, or Table 18 and Table 19); \(S_{\text{eff,BS/RS}}\) and \(S_{\text{eff,FAP}}\) are the cellular spectral efficiency of the RS-based network and the FAP-based network, respectively, which results taken from Table 12.

Since the transmission time allocation is not optimized to have an homogeneous cellular spectral efficiency (it means cellular spectral efficiencies of each network to be equal in (132)), depending on the criterion used to optimized the transmission time allocation the cellular spectral efficiency of the FAP-based network or the BS/RS-assisted network will predominate in the computation of the system cellular spectral efficiency.

7.4.4.1 System performance based on average spectral efficiency per user

Following criterion 1 detailed in section 7.4.3.1, next figures display the system cellular spectral efficiency and the outage rate of the whole system when the density of FAP increases (i.e. the number of UE served by FAP increases).

In all figures below, the ‘dotted line’ displays the system cellular spectral efficiency that will be achieved with the optimum transmission time allocation (before the quantification). The ‘solid line’ represents the system cellular spectral efficiency when the transmission time has been adapted to the LTE-A subframes durations over 2 LTE-A frames (after the quantification).

Figure 38 shows the system cellular spectral efficiency for \(k_1=1\) (left figure) and for \(k_1=10\) (right figure), when assuming an ideal backhaul for the FAP-based transmissions. Figure 39 shows the system cellular spectral efficiency for \(k_1=1\) (left figure) and for \(k_1=10\) (right figure), when assuming a non-ideal backhaul of 100Mbps for the FAP-based transmissions. When comparing both, it can be observed that as \(k\) increases higher system spectral efficiency can be achieved, because more priority is given to the users attached to a FAP. The presence of RS complements the deployment of FAPs in the sense that higher spectral efficiency is achieved as compared to the case where mobile terminals receives directly from the BS. In other words, all users are better served.

Notice that in Figure 38, the difference in terms of cellular spectral efficiency between using ‘relayed CoMP-JP’ and the other strategies is more notable for \(k_1=10\), because when \(k_1=10\) each transmission strategy on the BS/RS-based network allows for different transmission time allocation (see Table 16) while when \(k_1=1\) transmission time allocation are more similar (see Table 14). For \(k_1=10\), more time can be devoted for the FAP-based transmissions in the case ‘FAP & Relayed CoMP-JP’, thus achieving an increased system cellular spectral efficiency which explicates the difference.

When comparing results to an ideal backhaul link (Figure 38) and a non-ideal backhaul (Figure 39), it is shown that when the backhaul is non-ideal it strongly reduces the system cellular spectral efficiency, since the backhaul affects to the FAP users with best quality propagation conditions which are ones who contribute more to the system cellular spectral efficiency.

Moreover, comparing the system spectral efficiency in transmission strategies based on CoMP-JP with and without RS (‘FAP & Relayed CoMP-JP’ and ‘FAP & CoMP-JP’ in legends), it can be observed that a relay-based transmission can complement the FAP deployment and helps to improve the system spectral efficiency.
Figure 38: System cellular spectral efficiency vs. FAP density for $k_1=1$ (left) and $k_1=10$ (right) for an ideal backhaul link quality.

Figure 39: System cellular spectral efficiency vs. FAP density for $k_1=1$ (left) and $k_1=10$ (right) for FTTB@100Mbps backhaul link quality.

Figure 40 and Figure 41 show the outage rate for the worst 5% users on the whole system for $k_1=1$ (left figures) and for $k_1=10$ (right figures), when assuming and ideal backhaul or a non ideal backhaul, respectively.

Figure 42 and Figure 43 show the outage rate for the worst 15% users on the whole system for $k_1=1$ (left figures) and for $k_1=10$ (right figures), when assuming and ideal backhaul or a non ideal backhaul, respectively.

In all the figures (Figure 40, Figure 41, Figure 42 and Figure 43), it can be observed that deploy RS significantly helps to improve the system coverage (for both indoor and outdoor users) and improve the service to those users without a serving FAP, as the outage rate is higher for both deployments with relays (blue and red lines) compared to the deployment without relays (green line). However, for high density FAP deployments, it can be observed that deploy RS is not so much useful in terms of system outage rate the system, because for a 100% of the users served by FAPs the outage is significantly higher (see Table 12). So, RS-based transmission has an important effect for low FAP density deployments.

Since the transmission time is adjusted to have a fixed relation between the spectral efficiencies per user of each network, in general, the outage rate of the whole system is given by the worst users of the BS/RS-based network. For that reason, results with an ideal backhaul link and a non-ideal backhaul are nearly the same. However, the outage rate results differ slightly for high density FAP deployment (around 80-90%) because the time devoted for the BS/RS-based network is lower when the backhaul quality is FTTB@100Mbps. This implies that results with this backhaul are a bit lower.
When comparing results in outage rate for $k_1=1$ and $k_1=10$, it can be observed that there is a higher difference between deploy relay stations (blue and red lines) or not (green line) for the case $k_1=1$ than for $k_1=10$. Moreover, the system outage rate is higher with $k_1=1$ since it implies a homogeneous spectral efficiency per user and less priority is given to the users attached to a FAP. This behaviour is always observed except in the case of the computation of the 15% outage rate for a deployment with 90% of the users attached to a FAP (see Figure 42 and Figure 43); in that case, the 15% of the population with the worst service is also formed necessarily by the users served by a FAP, which explicates this particular case. Therefore, to conclude, the system performance as function of parameter $k_1$ allows an enhancement of the system cellular spectral efficiency when $k_1$ is increased while small losses in the outage rate can be appointed. Accordingly to simulation results, the best selection from the network operator’s point of view, would be $k_1=10$.

Figure 40: 5% Outage rate vs. FAP density for $k_1=1$ (left) and $k_1=10$ (right) for an ideal backhaul link quality.

Figure 41: 5% Outage rate vs. FAP density for $k_1=1$ (left) and $k_1=10$ (right) for FTTB@100Mbps backhaul link quality.
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7.4.4.2 System performance based on time allocated per user

According to the second criterion for the transmission time allocation (see section 7.4.3.2), next figures display the system cellular spectral efficiency and the outage rate of the whole system when the density of FAP increases (i.e. the number of UE served by FAP increases).

In all figures below, the ‘dotted line’ displays the system cellular spectral efficiency that will be achieved with the optimum transmission time allocation (before the quantification). The ‘solid line’ represents the system cellular spectral efficiency when the transmission time has been adapted to the LTE-A subframe durations over 2 LTE-A frames (after the quantification).

Figure 44 shows the system cellular spectral efficiency for $k_2=1$ (left figure) and $k_2=2$ (right figure), when assuming an ideal backhaul for the FAP-based transmissions. Figure 45 shows the system cellular spectral efficiency for $k_1=1$ (left figure) and $k_2=2$ (right figure), when assuming a non-ideal backhaul of 100Mbps for the FAP-based transmissions.

When comparing both, it can be observed that as $k$ increases lower system spectral efficiency can be achieved, because less time is given to the users attached to a FAP. The presence of RS complements the deployment of FAPs in the sense that higher spectral efficiency is achieved as compared to the case where mobile terminals receives directly from the BS. In other words, all users are better served.

When assuming a backhaul quality of FTTB@100Mbps it reduces nearly by half the system cellular spectral efficiency compared to the ideal backhaul quality, since the major influence in
the system cellular spectral efficiency is given by the FAP-based network which allows for higher cellular spectral efficiencies.

Figure 44: System cellular spectral efficiency vs. FAP density for $k_2=1$ (left) and $k_2=2$ (right) for an ideal backhaul link quality.

Figure 45: System cellular spectral efficiency vs. FAP density for $k_2=1$ (left) and $k_2=2$ (right) for FTTB@100Mbps backhaul link quality.

Figure 46 and Figure 47 show the outage rate for the worst 5% users on the whole system for $k_2=1$ (left figures) and for $k_2=2$ (right figures), when assuming an ideal backhaul or a non ideal backhaul, respectively.

Figure 48 and Figure 49 show the outage rate for the worst 15% users on the whole system for $k_2=1$ (left figures) and for $k_2=10$ (right figures), when assuming an ideal backhaul or a non ideal backhaul, respectively.

In all the figures showing the outage rate, it can be observed the same performance that in previous section when the transmission time was allocated to have a fixed relation between the spectral efficiency per user (see section 7.4.4.2): the outage rate is higher for both deployments with relays (blue and red lines) compared to the deployment without relays. So, deploy RS significantly allows to improve the system coverage and the service to those users without a serving FAP. And, this fact is more remarkable for low density FAP deployments, since for high density FAP deployments it limits the outage rate that can be achieved by the FAP-based transmissions (see Table 12 for 100% of the users served by FAPs).

When comparing results of the outage rate with an ideal backhaul quality and a non-ideal backhaul quality of FTTB@100Mbps (Figure 46 and Figure 47), it can be observed that results for the 5% are exactly the same because the outage rate is given by the worst users of the BS/RS-based network and the transmission time allocation does not depend on the backhaul.
quality. However, when comparing the results for the 15% worst users (Figure 48 and Figure 49), the outage rate slightly differs for high density FAP deployments (90% of the users served by FAPs), because the 15% of the population with the worst service is also formed necessarily by the users served by a FAP, which service is different for an ideal backhaul link quality than for a non-ideal backhaul link quality (see Table 12). Notice that in the non-ideal backhaul quality case (Figure 49) all three lines converge to the same value, it means that the outage rate is given by the transmission rate of the FUEs.

When comparing results in outage rate for \( k_2=1 \) and \( k_2=2 \), the system outage rate is slightly higher with \( k_2=2 \) since more time is given to the users in the BS/RS network. This behaviour is always observed except in the case of the computation of the 15% outage rate for a deployment with 90% of the users attached to a FAP, in which case the outage rate is affected by the users served by a FAP, which spectral efficiencies per user are higher for \( k_2=1 \) (as more time is devoted to them) and, for that reason the opposite behaviour is observed. Nevertheless, in conclusion, the gains in the outage rate when increasing \( k_2 \) are very lower compared to losses in the system cellular spectral efficiency.

![Figure 46: 5% Outage rate vs. FAP density for \( k_2=1 \) (left) and \( k_2=2 \) (right) for an ideal backhaul link quality.](image)

![Figure 47: 5% Outage rate vs. FAP density for \( k_2=1 \) (left) and \( k_2=2 \) (right) for FTTB@100Mbps backhaul link quality.](image)
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Figure 48: 15% Outage rate vs. FAP density for $k_2=1$ (left) and $k_2=2$ (right) for an ideal backhaul link quality.

Figure 49: 15% Outage rate vs. FAP density for $k_2=1$ (left) and $k_2=2$ (right) for FTTB@100Mbps backhaul link quality.
8 CONCLUSIONS

The objective of this project is to explore and evaluate new system architectures for next generation cellular systems, by developing new system deployments and then deriving algorithms for the resource allocation with QoS requirements for the downlink. Section 2 introduces the modulation and the multiple access modes used. In section 3, the propagation channel model is characterized. Section 4 provides the simulation environment that will be considered for the cell deployment and the user’s deployment, modeling two different scenarios in which the most suitable system architecture is evaluated. Section 5 evaluates the performance at the system level of Cooperative Multi-point Joint Processing (CoMP-JP) for outdoor homogeneous scenarios. In section 6, a RS-based cellular system deployment is considered for also homogeneous outdoor scenarios. A study of the combination of CoMP-JP and RS-based networks is presented and different solutions for the resource allocation are derived. At last, in section 7 a tentative tradeoff analysis of the femto-relays deployment is developed for hotspot scenarios.

In the CoMP-JP performance evaluation, various coordination types based on CoMP-JP and different precoding structures have been evaluated. In all cases, the performance is compared to the conventional cellular networks without BSs coordination for outdoor homogeneous scenarios, which shows that CoMP-JP is able to reduce inter-cell interference and improving significantly the downlink capacity. On the one hand, regarding the BD-ZF precoding matrix, it is shown that the best solution is almost always CoMP-JP full coordination. Partial coordination achieves a higher transmission rate for some users in the cell-edge, even the gain over the full coordination case is not so remarkable. On the other hand, sub-optimal and low-complexity precoding structures are proposed to maximize the user’s transmission rate under per-BS power constraints, which gains in terms of cellular spectral efficiency and cell-edge spectral efficiency are slightly lower than the optimum solution. Finally, modulation and coding schemes from the LTE-A are also considered as a constraint to the resource allocation problem. It is observed that higher order modulation and coding schemes could provide an enhanced system performance for low ISD deployments.

Further work is oriented to study coordination and cooperation between cell clusters, adopt backhaul capacity limitation constraints, implement MMSE precoders and receivers instead of BD-ZF for the multicarrier case and extend the cooperative MIMO channel to the case without synchronization of the BSs (X channel).

In the study of the combination of CoMP-JP and RS-based networks, optimal and suboptimal resource allocation algorithms for QoS-constrained relay-assisted cellular systems have been proposed, where cooperation between BS is appointed. Results show significant gains both in terms of cellular spectral efficiency and cell-edge spectral efficiency when compared to the non-cooperative relayed case. Afterwards, it is proposed to fix the duration of the relay-receive and relay-transmit phases to have stationary interference between cell clusters. In that case, optimal resource allocation can be achieved with a low-complexity algorithm solution which is developed and has a significantly reduced complexity: the number of variables to be optimized is independent of the number of transmission modes, which makes the problem easier to multiclasser systems. Results show that optimizing the duration of the relay-receive and relay-transmit phases is not critical, and still large gains both in terms of cellular spectral efficiency and outage rate are obtained. This observation facilitates the adoption of relay transmissions in next-generation wireless systems, as this guarantees the predictability of other cell-clusters interference within transmission frames.

Future work is focused on study more advanced relaying protocols, resource allocation for the uplink transmission and user’s grouping and scheduling strategies.

The tradeoff analysis in network deployments based on relay stations and femto access points in hotspot scenarios allows for important conclusions. Firstly, deploying relays improves the outage rate and the coverage for both indoor and outdoor users in hotspot scenarios, as significant gains in outage rate are obtained in the FAP-based deployment with RS compared to
the FAP-based deployment without RS. Secondly, it has been observed that RS-based deployments can complement FAP-based deployments to improve also the system cellular spectral efficiency for low density of FAPs. According to the simulations, the same system cellular spectral efficiency can be achieved for a network with RS as for a network without RS with a high density FAP deployment. Thirdly, results show that deploying RS is not useful any more at high density of FAPs both in terms of average spectral efficiency and outage rate, for the scenario defined where most of the traffic is generated by users inside or close to buildings. Finally, the suitability of applying CoMP-JP in the BS-RS transmission in a hotspot scenario has been proved, as enhanced results in cellular spectral efficiency are obtained compared to non-relayed transmission and compared to the relayed transmission with non-cooperative (CoMP-CS/CB) base stations.

Further work is oriented to develop a business model so as to evaluate, in the point of view of a network operator, the benefits of deploy relays and the complementarities between FAP-based and RS-based deployments.
9 REFERENCES

Access modes based on CoMP for relay transmissions in 4G systems


[22] 3GPP-LTE TSG-RAN WG1, Josep Vidal, Sandra Lagén, Mariana Goldhamer, document R1-112096 "Proposal of a CoMP study focused on relay-based networks", presented at 3GPP-LTE WG1 meeting #66, Athens, Greece, August 2011.


ANEXES
A. Path loss models

The path loss models used in this work are summarized in Table 20. The models can be applied in the frequency range of $2 - 6$ GHz and for different antenna heights. For each scenario, shadowing standard deviation $\sigma$ (defined in equation (5)) is given in the table. Note that the distribution of the shadow fading is log-normal (i.e. normal in logarithmic scale).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Path loss [dB]</th>
<th>Shadow fading std [dB]</th>
<th>Applicability range, antenna height default values</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS B5a WinnerII</td>
<td>$PL = 42.5 + 23.5 \log_{10}(d) + 28.0 + 20 \log_{10}(0.2f_c)$</td>
<td>$\sigma = 4$</td>
<td>$30 , m &lt; d &lt; 8000 , m$</td>
</tr>
<tr>
<td>NLOS C1 WinnerII</td>
<td>$PL = (44.9 - 6.55 \log_{10}(h_{BS}) - \log_{10}(d)) + 31.46 + 5.83 \log_{10}(h_{RS}) + 23 \log_{10}(0.2f_c)$</td>
<td>$\sigma = 8$</td>
<td>$50 , m &lt; d &lt; 5000 , m$</td>
</tr>
<tr>
<td>C2 Winner II LOS</td>
<td>$PL = 26 \log_{10}(d) + 39 + 20 \log_{10}(f_c)$</td>
<td>$\sigma = 4$</td>
<td>$d'_{BP,BM} &lt; d &lt; 3000 , m$</td>
</tr>
<tr>
<td>C2 Winner II NLOS</td>
<td>$PL = 40 \log_{10}(d) + 13.47 - 14 \log_{10}(h_{RS}) - 18 \log_{10}(h_{UE}) + 6 \log_{10}(0.2f_c)$</td>
<td>$\sigma = 6$</td>
<td>$d'_{BP,BM} &lt; d &lt; 3000 , m$</td>
</tr>
<tr>
<td>C4 WinnerII</td>
<td>$PL = PL_{C2}(d_{iso} + d_h) + 0.5 \log_{10}(d_{iso}) + 17.4 - 0.8 h_{UE}^3$</td>
<td>$\sigma = 10$</td>
<td>$50 , m &lt; d &lt; 5000 , m$</td>
</tr>
<tr>
<td></td>
<td>where $PL_{C2}$ is the pathloss function of C2 LOS/NLOS scenario.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Micro (UMi) LOS</td>
<td>$PL = 22.0 \log_{10}(d) + 28.0 + 20 \log_{10}(f_c)$</td>
<td>$\sigma = 3$</td>
<td>$10 , m &lt; d &lt; d'_{BP,BM}^{10}$</td>
</tr>
<tr>
<td></td>
<td>$PL = 40 \log_{10}(d) + 7.8 - 18 \log_{10}(h_{BS}) - 18 \log_{10}(h_{UE}) + 2 \log_{10}(f_c)$</td>
<td>$\sigma = 3$</td>
<td>$d'_{BP,BM} &lt; d &lt; 5000 , m$</td>
</tr>
<tr>
<td></td>
<td>$h_{RS} = 10 , m^3, h_{UE} = 1.5 , m^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Micro (UMi) NLOS</td>
<td>$PL = 36.7 \log_{10}(d) + 22.7 + 26 \log_{10}(f_c)$</td>
<td>$\sigma = 4$</td>
<td>$10 , m &lt; d &lt; 2000 , m$</td>
</tr>
<tr>
<td></td>
<td>$h_{RS} = 10 , m, h_{UE} = 1-2.5 , m$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Macro (UMa) LOS</td>
<td>$PL = 22.0 \log_{10}(d) + 28.0 + 20 \log_{10}(f_c)$</td>
<td>$\sigma = 4$</td>
<td>$10 , m &lt; d &lt; d'_{BP,BM}^{10}$</td>
</tr>
<tr>
<td></td>
<td>$PL = 40 \log_{10}(d) + 7.8 - 18 \log_{10}(h_{BS}) - 18 \log_{10}(h_{UE}) + 2 \log_{10}(f_c)$</td>
<td>$\sigma = 4$</td>
<td>$d'_{BP,BM} &lt; d &lt; 5000 , m$</td>
</tr>
<tr>
<td></td>
<td>$h_{BS} = 25 , m^3, h_{UE} = 1.5 , m^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Macro (UMa) NLOS</td>
<td>$PL = 161.04 - 7.1 \log_{10}(h) + 7.5 \log_{10}(h) (\log_{10}(h_{BS}) - 2.37 - 3.7 (h/h_{BS})) \log_{10} (h_{BS}) + (43.42 - 3.1 \log_{10} (h_{BS})) (\log_{10} (d)) - 3.2 (\log_{10} (11.75 h_{UE}))^2 - 4.97)$</td>
<td>$\sigma = 6$</td>
<td>$10 , m &lt; d &lt; 5000 , m$</td>
</tr>
<tr>
<td></td>
<td>$h_{BS} = 25 , m, h_{UE} = 1.5 , m$, $W = 20 , m, h = 20 , m$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The applicability ranges: $5 , m &lt; h &lt; 50 , m$, $5 , m &lt; W &lt; 50 , m$, $10 , m &lt; h_{BS} &lt; 150 , m$, $1 , m &lt; h_{UE} &lt; 10 , m$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1) Break point distance \(d'_{BP,BM} = 4 \ h'_BS \ h'_UE \ f_c/c\) and \(d'_{BP,RS} = 4 \ h'_RS \ h'_UE \ f_c/c\), where \(f_c\) is the centre frequency in Hz, \(c=3.0\times10^8\) m/s is the propagation velocity in free space, and \(h'_BS, h'_RS\) and \(h'_UE\) are the effective antenna heights at the BS, the RS and the UE, respectively.

2) The effective antenna heights \(h'_BS, h'_RS\) and \(h'_UE\) are computed as follows: \(h'_BS = h_{BS} - 1.0\) m, \(h'_RS = h_{RS} - 1.0\) m, \(h'_UE = h_{UE} - 1.0\) m, where \(h_{BS}, h_{RS}\) and \(h_{UE}\) are the actual antenna heights, and the effective environment height in urban environments is assumed to be equal to 1.0 m.

3) \(d_{out}\) is the distance between the outdoor terminal and the point on the wall that is nearest to the indoor terminal, \(d_{in}\) is the distance from the wall to the indoor terminal.

The line-of-sight (LOS) probabilities for C2 from Winner II and UMa and UMi from ITU models are given in Table 21. Those probabilities are used only for system level simulations.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>LOS probability as a function of distance (d) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2</td>
<td>(P_{LOS} = \min(18/d,1) \cdot (1 - \exp(-d/63)) + \exp(-d/63))</td>
</tr>
<tr>
<td>UMi</td>
<td>(P_{LOS} = \min(18/d,1) \cdot (1 - \exp(-d/36)) + \exp(-d/36))</td>
</tr>
<tr>
<td>UMa</td>
<td>(P_{LOS} = \min(18/d,1) \cdot (1 - \exp(-d/63)) + \exp(-d/63))</td>
</tr>
</tbody>
</table>
B. Proof of the optimal MIMO symbol precoding matrix structure when single power constraint

When we want to maximize the UEs’ transmission rates subject to a single power constraint (usually referred to the sum power, as the sum of the power used to transmit from all BSs), the optimal MIMO symbol precoding matrix structure for matrices $S_i$ is obtained from the following maximization problem. If we consider $T_i = SS_i^H$, the weighted sum-rate maximization problem for the downlink transmission in CoMP-JP with BD-ZF precoding and single power constraint can be written as follows:

$$\begin{align*}
\max_{T_i} & \quad \sum_{i=1}^{M} \mu_i \log_2 \left| I + N_i^{-1/2} H_i V_i T_i V_i^H H_i^H N_i^{-1/2} \right| \\
\text{s.t.} & \quad \left\{ \sum_{i=1}^{M} \text{tr} (T_i) - BP_{\max} \leq 0 \\
& \quad T_i \geq 0 \ , T_i = T_i^H \quad i = 1, \ldots, M \right. 
\end{align*}$$  \tag{133}

The optimization is done over the set of positive definite matrices $T_1, \ldots, T_M$, which need to be positive definite matrices and Hermitian matrices (as it is imposed in the second constraint).

It is easy to verify that (133) is a convex optimization problem, since the objective function is concave over $T_i$’s and all the constraints specify a convex set over $T_i$’s. Then, (133) can be solved using standard convex optimization techniques, e.g., interior-point method [32]. However, the optimal structure for $T_i$ can be found using Lagrange duality methods.

The Lagrangian function of (133) can be written as:

$$L\left(\{T_i\}, \gamma\right) = \sum_{i=1}^{M} \mu_i \log_2 \left| I + N_i^{-1/2} H_i V_i T_i V_i^H H_i^H N_i^{-1/2} \right| - \gamma \sum_{i=1}^{M} \text{tr} (T_i) + \gamma BP_{\max}$$  \tag{134}

where $\{T_i\}$ denotes the set of $T_i$’s and $\gamma$ denotes the non-negative dual variable associated to the sum power constraint.

If we formulate the Lagrange dual function of (133):

$$g \left( \gamma \right) = \max_{T_i} L \left( \{T_i\}, \gamma \right)$$  \tag{135}

we can define the dual problem of (133) as:

$$\max_{\gamma \geq 0} g \left( \gamma \right)$$  \tag{136}

Since problem in (133) is convex and satisfies the Slater’s condition [32], the duality gap between the optimal objective value of (133) and that of (136) is zero. Then, (133) can be solved equivalently by solving the problem in (136).

Now, we focus on solving $\{T_i\}$ for a fixed value of $\gamma$. From (133), it can be observed that the maximization problem can be separated into $M$ independent subproblems (on for each UEs):

$$\max_{T_i} \mu_i \log_2 \left| I + N_i^{-1/2} H_i V_i T_i V_i^H H_i^H N_i^{-1/2} \right| - \gamma \text{tr} (T_i)$$  \tag{137}

In order to find the optimal solution for (137), we can apply Hadamard’s inequality [24]. Hadamard’s inequality is used to solve problems which consist on maximizing the determinant of a matrix, subject to its trace. Note that, as the logarithm is an increasing function, it is the same maximizing the logarithm than the values inside it. Moreover, due to the fact that $\log(1 + AB) = \log(1 + BA)$, we can apply Hadamard’s inequality. Hadamard’s inequality demonstrates that the optimal solution for those problems is a diagonal matrix for the values
inside the determinant. In other words, the optimal solution is such that diagonalizes 
\[ [I + N_i^{-1/2}H_iV_iT_iV_i^H\Lambda_iU_i^H], \]
Therefore, if we consider the following (reduced) SVD:
\[ N_i^{-1/2}H_iV_i = U_i\Lambda_iW_i^H \] (138)
where \( \Lambda_i = \text{diag}\{\lambda_{i1}, ..., \lambda_{im}\} \) is a \( m_i \times m_i \) diagonal matrix containing the eigenvalues of \( N_i^{-1/2}H_iV_i \), \( U_i \) is a unitary matrix containing the \( m_i \) left singular vectors and \( W_i \) is a unitary matrix containing the \( m_i \) right singular vectors of \( N_i^{-1/2}H_iV_i \), associated to the largest singular vectors.

Hence, the optimal solution for (137), for a fixed value of \( \gamma \), is:
\[ T_i^* = WP_iW_i^H \] (139)
where \( P_i \) is a \( m_i \times m_i \) diagonal matrix containing the power allocated to each symbol stream \( P_i = \text{diag}\{p_{i1}, ..., p_{im}\} \), whose optimal values are obtained by the standard water-filling algorithm as:
\[ p_{ij} = \left( K\mu_i - \frac{1}{\lambda_{ij}} \right)^+ \] (140)
where \( K \) is such that satisfies with equality the sum power constraint in (133):
\[ \sum_{i=1}^{M} tr(W_iP_iW_i^H) = \sum_{i=1}^{M} \sum_{j=1}^{m_i} p_{ij} = BP_{\text{max}} \]
In other words, the power allocation given by the water-filling algorithm is:
\[ p_{ij} = \left( \frac{BP_{\text{max}} + \sum_{i=1}^{M} \sum_{j=1}^{m_i} \frac{1}{\lambda_{ij}}}{\sum_{i=1}^{M} m_i\mu_i} \mu_i - \frac{1}{\lambda_{ij}} \right)^+ \] (141)
Note that the solution in (139) diagonalizes the values inside the determinant:
\[ \log_2[I + N_i^{-1/2}H_iV_iT_iV_i^H\Lambda_iU_i^H] = \log_2[I + \Lambda_iU_iW_i^HW_iP_iW_i^HW_i^H\Lambda_iU_i^H] \]
due to \( \log(I+AB) = \log(I+BA) \), \( W_i^HW_i = I \), \( U_i^HU_i = I \) and both matrices \( \Lambda_i \) and \( P_i \) are diagonal.

Also note that the optimal solution is independent of the lagrange multiplier associated to the sum power constraint \( \gamma \). But if we would like to find the optimal value for \( \gamma \) we should derive the Lagrangian function (134) over \( T_i^H \), and substitute the optimal structure of \( T_i^* \).

Finally, as \( P_i \) is a diagonal matrix, we can easily undo the initial variable change \( T_i = SS_i^H \), and the optimal MIMO precoding matrix \( S_i^* \) to maximize the weighted sum-rate subject to the sum power constraint is given by:
\[ S_i^* = WP_i^{1/2} \] (142)
C. Proof of the optimal MIMO symbol precoding matrix structure when per-BS power constraints

When we want to maximize the UEs’ transmission rates subject to per-BS power constraints, the optimal MIMO symbol precoding matrix structure for matrices $S_i$ is obtained from the following maximization problem. If we consider $T_i = S_iS_i^H$, the weighted sum-rate maximization problem for the downlink transmission in CoMP-JP with BD-ZF precoding and per-BS power constraints can be written as follows:

$$\begin{align*}
\text{maximize} & \quad \sum_{i=1}^{M} \mu_i \log_{2} \left| I + N_i^{-1/2} H_i V_iT_iV_i^H H_i^H N_i^{-H/2} \right| \\
\text{s.t.} & \quad \text{tr} \left( \sum_{i=1}^{M} B_{\gamma} V_iT_iV_i^H \right) - P_{\text{max}}^k \leq 0 \quad k = 1, \ldots, B \\
& \quad T_i \succeq 0 \quad T_i = T_i^H \quad i = 1, \ldots, M
\end{align*}$$

(143)

The optimization is done over the set of positive definite matrices $T_1, \ldots, T_M$, which need to be positive definite matrices and Hermitian matrices, as it is imposed in the second constraint.

It is easy to verify that (143) is a convex optimization problem, since the objective function is concave over $T_i$’s and all the constraints specify a convex set over $T_i$’s. Then, (143) can be solved using standard convex optimization techniques, e.g., interior-point method [32]. However, as demonstrated in [35], the optimal structure for $T_i$ can be found using Lagrange duality methods.

The Lagrangian function of (143) can be written as:

$$L\left(\{T_i\}, \{\gamma_k\}\right) = \sum_{i=1}^{M} \mu_i \log_{2} \left| I + N_i^{-1/2} H_i V_iT_iV_i^H H_i^H N_i^{-H/2} \right| - \text{tr} \left( \sum_{i=1}^{M} B_{\gamma} V_iT_iV_i^H \right) + \sum_{k=1}^{B} \gamma_k^i P_{\text{max}}^k$$

(144)

where $B_{\gamma} = \sum_{i=1}^{B} \gamma_k^i B_k = \text{diag} \left( [\gamma_1, \gamma_2, \ldots, \gamma_B] \right) \otimes I_{M \times M}$ (where $\otimes$ denotes the Kronecker product). $\{T_i\}$ denotes the set of $T_i$’s and $\{\gamma_k\}$ denotes the set of non-negative dual variables $\gamma_k$’s.

If we formulate the Lagrange dual function of (143):

$$g \left( \{\gamma_k\} \right) = \text{maximize} \quad L\left(\{T_i\}, \{\gamma_k\}\right)$$

(145)

we can define the dual problem of (143) as:

$$\max_{\gamma_k \geq 0} \quad g \left( \{\gamma_k\} \right)$$

(146)

Since (143) is convex and satisfies the Slater’s condition [32], the duality gap between the optimal objective value of (143) and that of (146) is zero. Then, (143) can be solved equivalently by solving (146).

Now, we focus on solving $\{T_i\}$ for a set of fixed $\{\gamma_k\}$. From (143), it can be observed that the maximization problem can be separated into $M$ independent subproblems (on each UEs):

$$\begin{align*}
\text{maximize} & \quad \mu_i \log_{2} \left| I + N_i^{-1/2} H_i V_iT_iV_i^H H_i^H N_i^{-H/2} \right| - \text{tr} \left( B_{\gamma} V_iT_iV_i^H \right) \\
\end{align*}$$

which, due to the fact that $\text{tr}(AB) = \text{tr}(BA)$, can also be expressed as:

$$\begin{align*}
\text{maximize} & \quad \mu_i \log_{2} \left| I + N_i^{-1/2} H_i V_iT_iV_i^H H_i^H N_i^{-H/2} \right| - \text{tr} \left( V_i^H B_{\gamma} V_iT_i \right)
\end{align*}$$

(147)
If we define \( T_i = (V_i^H B_i V_i)^{1/2} T_i (V_i^H B_i V_i)^{1/2} \) the maximization problem in (147) can be reformulated as:

\[
\max_{T_i} \mu_i \log I + N_i^{-1/2} H_i V_i \left( V_i^H B_i V_i \right)^{1/2} \hat{\mathbf{T}} \left( V_i^H B_i V_i \right)^{1/2} V_i^H H_i N_i^{-1/2} - \text{tr} \left( \hat{\mathbf{T}} \right) \tag{148}
\]

In order to find the optimal solution for (148), we can apply Hadamard’s inequality [24]. Hadamard’s inequality is used to solve problems which consist on maximizing the determinant of a matrix, subject to its trace. Note that, as the logarithm is an increasing function, it is the same maximizing the logarithm than the values inside it. Moreover, due to the fact that \( \log(1+AB) = \log(1+BA) \), we can apply Hadamard’s inequality. Hadamard’s inequality demonstrates that the optimal solution for those problems is a diagonal matrix for the values inside the determinant. In other words, the optimal solution is such that diagonalizes \( N_i^{-1/2} H_i V_i \left( V_i^H B_i V_i \right)^{1/2} \hat{\mathbf{T}} \left( V_i^H B_i V_i \right)^{1/2} V_i^H H_i N_i^{-1/2} \). Therefore, if we consider the following (reduced) singular value decomposition (SVD):

\[
N_i^{-1/2} H_i V_i \left( V_i^H B_i V_i \right)^{1/2} = \hat{U}_i \hat{\Lambda}_i \hat{W}_i^H
\]

where \( \hat{\Lambda}_i = \text{diag}(\hat{\lambda}_1, \ldots, \hat{\lambda}_m) \) is a \( m \times m \) diagonal matrix containing the eigenvalues, \( \hat{U}_i \) is a unitary matrix containing the \( m \) left singular vectors and \( \hat{W}_i \) is a unitary matrix containing the \( m \) right singular vectors of \( N_i^{-1/2} H_i V_i \left( V_i^H B_i V_i \right)^{1/2} \).

Then, the optimal solution for (148), for a fixed set of \( \{ \gamma_k \} \), is:

\[
\hat{T}_i = \hat{W}_i \hat{P}_i \hat{W}_i^H
\]

where \( \hat{P}_i = \text{diag}(\hat{p}_{i1}, \ldots, \hat{p}_{im}) \) is a diagonal matrix, which diagonal values are obtained from the standard water-filling algorithm:

\[
\hat{p}_{ij} = \left( \frac{\mu_i}{\ln(2)} - \frac{1}{\lambda_{ij}} \right)^{-2} \quad i = 1, \ldots, M \quad j = 1, \ldots, m_i
\]

Note that the solution in (150) diagonalizes the values inside the determinant:

\[
\log I + N_i^{-1/2} H_i V_i \left( V_i^H B_i V_i \right)^{1/2} \hat{\mathbf{T}} \left( V_i^H B_i V_i \right)^{1/2} V_i^H H_i N_i^{-1/2} = \\
= \log I + \hat{U}_i \hat{\Lambda}_i \hat{W}_i^H \hat{P}_i \hat{W}_i^H \hat{W}_i \hat{\Lambda}_i \hat{U}_i^H = \log I + \hat{\Lambda}_i \hat{P}_i \hat{\Lambda}_i^H
\]

due to \( \log(1+AB) = \log(1+BA) \), \( \hat{W}_i^H \hat{W}_i = I \), \( \hat{U}_i^H \hat{U}_i = I \) and both matrices \( \hat{\Lambda} \) and \( \hat{P}_i \) are diagonal.

Finally, if we undo the variable change that relates \( \hat{T}_i \) with \( T_i \), we obtain:

\[
T_i = (V_i^H B_i V_i)^{1/2} \hat{W}_i \hat{P}_i \hat{W}_i^H \left( V_i^H B_i V_i \right)^{1/2} \tag{152}
\]

Once obtained the optimal solution for \( \{ T_i \} \) for a set of fixed \( \{ \gamma_k \} \), we need to find \( \gamma_k \) for \( k = 1, \ldots, B \) to solve the whole problem (143). Note that when the optimal solution for \( \{ \gamma_k \} \) is obtained, the corresponding solution in (152) becomes optimal for (143). Then, we need to initialize \( \{ \gamma_k \} \) properly and actualize the Langrange multipliers \( \gamma_k \) for \( k = 1, \ldots, B \), step by step, accordingly to the following subgradient:

\[
d_k = \text{tr} \left( \sum_{i=1}^{M} B_i V_i T_i V_i^H \right) - P_{\text{max}}^k
\]

The subgradient is computed in order to update the set of variables \( \{ \gamma_k \} \) properly. The correct procedure is: once calculated the optimal values for \( T_i \) from (152) for a fixed set \( \{ \gamma_k \} \), we should compute the subgradient \( d_k \) with the obtained \( T_i \), and it will indicates us how to update the set of \( \{ \gamma_k \} \) for the next iteration. If the subgradient \( d_k \) is positive, it indicates that the \( k \)-th
BSs is using more power than the allowed $P_{\text{max}}$, so we have to increase or decrease the value of $\gamma_k$ in order not to exceed the allowed power. As $T_i^*$ depends on all the set $\{\gamma_k\}$ we cannot decide how to actualize each $\gamma_k$, but we can update all of them simultaneously by using, for example, the Ellipsoid method [34].

After all, we have to undo the initial variable change: $T_i = S_i S_i^H$. Hence, the optimal MIMO symbol precoding matrix $S_i^*$ to maximize the weighted sum-rate subject to per-BS power constraints is given by:

$$S_i^* = (V_i^H B_i^* V_i)^{1/2} \hat{W}_i \hat{P}_i^{1/2}$$

(154)

Note that $S_i^*$ consists of non-orthogonal columns if $B_i^*$ is a non-identity diagonal matrix (i.e., the optimal $\{\gamma_k\}$ are not all equal).

Moreover, it can be verified that for the sum-power constraint case (see Annex B), $S_i^*$ consists of orthogonal columns (beamforming vectors) since $V_i^H V_i = I$ and its structure is independent of $\gamma$. 
D. Simulation results

Two fundamental measures are adopted: cellular spectral efficiency ($S_c$), as the sum rate of the users in a cell area averaged over many deployments, and cell-edge spectral efficiency ($r_{ce}$), as the peak achievable rate of the $\epsilon$-percentile worst users in the macrocell over many deployments.

Considering an hexagonal deployment and 3 sectors per BSs, if $M=6$ users (or UEs) are deployed in the macrocell then 2 users are served in a cell area. Consequently, for the general case, the cellular spectral efficiency is computed as:

$$S_c = \frac{1}{3} \sum_{i=1}^{M} r_i \quad [\text{bits/s/Hz/cell}]$$

(155)

and the cell-edge spectral efficiency (also called outage rate) is obtained, in terms of $[\text{bits/s/Hz}]$, from:

$$\epsilon = \Pr \left( r_i \geq r_{ce} \left( \epsilon \right) \mid i = 1,\ldots,M \right) = 0.95$$

(156)

Both measures capture most of the benefits offered by the coordination of BSs and relay-based transmissions.
E. Attenuated and truncated Shannon capacity

Considering the basic LTE-A downlink physical layer parameters in Table 22:

<table>
<thead>
<tr>
<th>Table 22: LTE-A downlink physical layer parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Carrier frequency</td>
</tr>
<tr>
<td>System bandwidth</td>
</tr>
<tr>
<td>OFDM parameters</td>
</tr>
<tr>
<td>Channel model</td>
</tr>
<tr>
<td>Modulation and coding schemes (MCS)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Encoding scheme</td>
</tr>
<tr>
<td>Channel estimation</td>
</tr>
<tr>
<td>Speed</td>
</tr>
</tbody>
</table>

The spectral efficiency is presented in Figure 50 as a function of the SNR for each MCS listed in Table 22. It also shows the Shannon bound (in grey colour), which represents the maximum theoretical throughput than can be achieved over an AWGN channel for a given SNR.

![Figure 50: Spectral efficiency as a function of SNR for the LTE-A MCS](image)

Figure 51 presents the modified Shannon capacity expression in (65) for one transmit antenna. It is also truncated according to the high spectral efficiency given by the hard MCSs (64-QAM and code rate 4/5), which allows 4.8bits/s/Hz at high SNR.

![Figure 51: Spectral efficiency for the LTE-A MCS and its associated curve fitting](image)
F. LTE-A frame configuration

In order to fix the duration of the relay-receive and the relay-transmit phases, we have to consider the duration of the LTE-A subframes.

In LTE-A the duration of a frame is 10ms, which can be split on 10 subframes. One subframe is always allocated for synchronism. Therefore, the number of subframes for data transmission is limited to 9 in 10ms.

Moreover, the frame structure depends on the duplexing mode (TDD or FDD). In TDD the situation is worse, as the 9 subframes shall be also split between uplink (UL) and downlink (DL).

Table 23 details the frame structure for different uplink-downlink configurations. The subframe destined to synchronization is denoted with S in the table. U and D denote the UL subframe and the DL subframe, respectively. In some configurations, two subframes are required to synchronize UL and DL.

<table>
<thead>
<tr>
<th>Uplink-Downlink configuration</th>
<th>Downlink-to-Uplink Switch-point periodicity</th>
<th>Subframe number</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5 ms</td>
<td>D S U U U D S U U</td>
</tr>
<tr>
<td>1</td>
<td>5 ms</td>
<td>D S U U D D S U U</td>
</tr>
<tr>
<td>2</td>
<td>5 ms</td>
<td>D S U D D S U D</td>
</tr>
<tr>
<td>3</td>
<td>10 ms</td>
<td>D S U U U D D D D</td>
</tr>
<tr>
<td>4</td>
<td>10 ms</td>
<td>D S U U D D D D D</td>
</tr>
<tr>
<td>5</td>
<td>10 ms</td>
<td>D S U D D D D D D</td>
</tr>
<tr>
<td>6</td>
<td>5 ms</td>
<td>D S U U U D S U U</td>
</tr>
</tbody>
</table>

In mobile wireless data transmission, generally, more time is devoted to DL transmission than for the UL transmission. For that reason, we consider configuration 5 in Table 23, in which case 8 subframes can be allocated to DL and 1 for the UL.

This way, from the 8 subframes devoted for the DL, we could assign subframes to:
- BS-RS transmission
- RS-UE transmission

Otherwise, in the femto-relays tradeoff analysis we could assign subframes to:
- RS-assisted transmissions
- FAP-based transmissions