ICT-248891 STP FREEDOM

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

D5.2

System interference management evaluation

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Abstract:

The scope of D5.2 is to face the problem of network planning in the presence of a dense, inhomogeneous distribution of FAPs by managing the femto population as a whole. Different methods and benefits from a clustering strategy are evaluated, together with the implementation at system level of some optimization methods devised in 3A2. The sensing capability of the single FAPs is paired to the sharing of slowly varying metrics through the ISP backhaul as the basis to adopt resources allocation strategies for a realistic interference environment. A full description of the software modules for D5.2 simulations includes coverage and traffic flow in the network. System performance has been tested for real geographic deployments, time-varying environments, and finally evaluating MBS traffic offload and QoS gained in that case. System-level simulations are completed with an analysis of the femto-based interference impact, realized from a LTE coverage simulator that is based on a simple MAC-layer abstraction.

Keyword list: Network planning, interference modeling

Executive Summary

The scope of this document is to address the impact of network planning for interference management by evaluating both the radio coverage and the cell performances when a set of MUEs and FUEs are present. Such issues are merged in the dynamic simulator which includes transmission events and traffic flows in the network, as well optimization strategies designed in 3A2.

A relevant part of activity 5A2 is given by the development of a simulation chain for evaluation of the macro+femto LTE coverage performance. It is composed of: controlled or random large-scale FAP deployments in synthetic and real geographical environments; prediction of 3D path-loss maps (in streets and in different building floors); prediction of the LTE downlink coverage (signal-to-interference maps and spectral efficiency maps); and finally, estimate of the delivered throughput and network capacity. Let us remark that these simulation tools support both the open and closed-access modes, and provide performance statistics for both FAP subscribers and non FAP subscribers.

The LTE coverage simulator makes simple assumptions on the interference modeling and does not consider, in particular, inter-cell interference coordination. The results must be viewed as a characterization of the useful and interference signal levels; or as a pessimistic reference giving the network performance that would be obtained in absence of any specific interference mitigation technique.

The coverage simulations are conducted in a large number of scenarios to investigate FAP deployments in urban corporate and suburban residential environments, in presence or absence of co-channel macro coverage (actually only the urban corporate deployment has been studied in absence of macro coverage). The impact of a FAP deployment is analyzed at different scales: in FAP vicinity, within the deployment floor, within the deployment building, in surrounding streets, or within a whole macro cell. Complementarily, several properties of the FAP deployment (density, location within the building and transmit power) and of FAP traffic are investigated. Part of the urban corporate simulations relies on real geographical map data and site-specific path-loss predictions, thus lead to very realistic results.

The coverage simulations provide outcomes towards the engineering rules elaborated in activity 6A2 and towards the 2A3 business model analysis.

Management of the network can be augmented by designing and evaluating clustering methods, in order to run faster management algorithms on selected sets of users. Assignment of power and/or band shows to be much more efficient when evaluating the impact of fast metric measurements. Indeed, optimization algorithms show far less complexity when run in parallel on sets of few units (less than 20) with respect to considering the network as a whole. Such simulations, including analysis of different cluster topologies and implementation of Genetic Optimization at system level, have been considered implementing both transmission events and network data flow.

Adaptive resource allocation algorithms have been proposed in D3.2 by incorporating a Markovian model of the macro-users interference activity and using alternative pricing mechanisms to allocate power in the joint time-frequency plane. The scheduling of these resource allocation algorithms has been considered on the LTE frame structure. We evaluated the data-rate loss for the max-rate game due to its running time: the time available for data transmission becomes shorter when a fraction of time slots is spent for letting the algorithm run and converge. The signaling overhead depends on two parameters: the accuracy required for the convergence of the algorithm, which is related to the number of iterations, and how often the algorithm is run. Then the number of time slots required for the running of the algorithm has been evaluated deriving its dependence on number of active FAPs and of iterations. The achievable rate decreases when increasing the frequency with which the resource allocation game is run. Furthermore, it is interesting to emphasize the predictive nature of the proposed allocation strategy: the knowledge of interference statistical parameters, if properly exploited

as in the proposed algorithms, yields a rate very similar to the ideal case assuming non-causal knowledge of the macro-users activity.

Complementarily to activity 5A1 (see [Freedom-D51]), the metrics measuring system performances have also been tested to different combinations of variable band allocations which could be of interest for a Mobile Network Operator (MNO). Moreover, a temporal variation of the environment and of the users' positions has been included in the system simulator.

The algorithms developed allow controlling events of transmission, related to the assignment of time slots in the LTE subframe, taking into account also data packets generated by applications running on mobile terminals and their encoding in the PRBs structure by the RRM scheduler.

The packet flow module, complemented with the transmission system dynamics, allows to evaluate the information data passing through the cell and the impact on all transmitters. A measurement of the QoS and traffic load has been put in relation to the energy needed to run a set of applications on UEs mobile terminals.

The overall simulator has been tested in several cases of interest which can be summarized as:

- Impact of clustering on possibility to extend optimization methods at system level in a reliable way, in order to manage also high number of users;
- Inclusion of a set of real environments, providing metrics also for the mapped scenarios, produced by SIR, with geographic deployments of buildings and users;
- Mobility of users and temporal changes in the environment around transmitters have been included and evaluated;
- Evaluation of the system performances for different cases of varying band usage: equipartition of band between MBS and femto network, considering a fixed spectrum allocation for the MBS and varying that of second tier, or fixing the band usage of the femto network and increasing that of the macro network;
- Evaluation of system performances when including a GO for power assignment of FUEs/FAPs to mitigate indoor interference;
- Quantification of the MBS offload when routing traffic of a set of Ues indoor through FAPs instead of through the macro network.

DISCLAIMER

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List of abbreviations & symbols

ACK	Acknowledge
APN	Access Point Name
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BS	Base Station
BW	Bandwidth
CDF	Cumulative Distribution Function
CRC	Cyclic Redundancy Check
CSG	Close Subscriber Group
CSIT	Channel State Information in Transmission
DF	Decode and Forward
DL	Downlink
ESM	Effective SNR Mapping
FAP	Femto Access Point
FCS	Frame Check Sequence
FDD	Frequency Division Duplex
FUE	Femto User Equipment
GA	Genetic Algorithm
GO	Genetic Optimization
LOS	Line Of Sight
LTE	Long Term Evolution
MBS	Macro Base Station
MCS	Modulation and Coding
MIMO	Multiple Input Multiple Output
MNO	Mobile Network Operator
MS	Mobile Station
MUE	Macro User Equipment
NACK	Not ACK
NLOS	Non Line Of Sight
OFDM	Orthogonal Frequency Division Modulation
OFDMA	Orthogonal Frequency Division Multiplexing Access
OWRC	One-Way Relay Channel
PER	Packet Error Rate
PPS	Packets Per Second
PS	Packet Scheduler
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RB	Resource Block
RE	Resource Element
RRM	Radio Resource Management
RS	Relay Station
RSSI	Received Signal Strength Indicator
RTP	Real Time protocol
SDU	Service Data Unit
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SSID	Service Set Identifier
TDD	Time Division Duplex
TDMA	Time division multiplexing access
TWRC	Two-Way Relay Channel
UDP	User Datagram Protocol

UE	User Equipment
UL	Uplink
VoIP	Voice over IP
WNO	Wireless Network Operator

1 INTRODUCTION

The purpose of this document is to analyze methods and solutions to address the problem of optimizing the presence of a dense, distributed and clustered population of femtocells within a core network with an approach basically different from the optimization (with selfish mechanisms) of each single femtocell interfered by the macro network.

Current femtocells face the interference problem at PHY level by implementing workarounds such as adaptive pilot power control, dynamic femtocell receiver gain management, mobile phone uplink power capping and extended femtocell receiver dynamic range (e.g. standards [TS25.104], [TR 25.820]). Indeed, actually implemented techniques on the market do not encompass any form of coordination/cooperation among the different entities and are basically selfish approaches tailored on a single device. On the opposite, a population of femtocells can be better viewed as spatially distributed and clustered resources that can be seen as either interference or useful resources, depending on the degree of coordination with the core network (topics spotted in WP3 and WP4, for reference, see [Freedom-D32], [Freedom-D33] and [Freedom-D41]).

The requirements in terms of computation load, increased traffic on the backhaul link and the constraints on maximum latency admitted to perform optimization adaptation for resources allocation can be considered from a system level point of view.

The task addressed in the current activity is to face the problem of network planning in presence of a dense, inhomogeneous distribution of FAPs. The target is not the best suited interference management for each single femtocell in the population (that is not scalable and can be very demanding in terms of requirements on the backhaul bandwidth), but the (sub)optimal management of the interference of the femto population as a whole, requiring a very limited amount of information flow among the involved parties.

The main goal foreseen within this framework is optimization with system scalability. In this sense, the network planning for the interference management is sub-optimal with respect to the methodologies developed in WP3, as in this approach some degree of optimality for each single femtocell is paid in the perspective of achieving major gains in terms of system scalability and fairness.

The purpose of this document is to answer the following questions:

a) Can the whole FAP deployment be represented as a set of clusters and under which criteria?
b) How does clustering affect network performances?
c) Can the RRM deal with aggregated metrics, referred to different clustering hierarchy?

The topic here addressed is to design new techniques based on the joint exploitation of the sensing capability of the single FAPs and on the sharing of aggregated and slowly varying metrics between the core network and the femtocells trough the ISP backhaul.

The scheduling on the LTE frame structure of distributed resource allocation algorithms using alternative pricing mechanisms to allocate power in the joint time-frequency plane has been considered in order to evaluate the loss on the data rate due to the running time of the iterative algorithm and to the frequency with which it is run. The number of time slots needed for the convergence of the algorithm depends on the number of iterations and the number of active FAPs. Furthermore by exploiting the statistical knowledge of the macro-user activity it has been shown that the proposed resource allocation game yields a rate very similar to the ideal case assuming perfect knowledge of the macro interference activity.

The analysis are based either on a set of scenarios designed in 2A1 for common FAPs deployments, either on some scenarios designed *ad hoc* for the current tasks. In both cases, the methodologies will be tested highlighting the requirements for the FAP deployment in terms of

- Network hardware (e.g., FAP gateway, IP backhaul)
- FAPs software (e.g., local processing load, sensing capabilities and dedicated channel for signaling).

This task will be based on the analysis and implementation of approaches such as (but not limited to) time/power/subcarriers allocation strategies with low reuse patterns of the radio resources.

System-level simulations are completed with an analysis of the femto-based interference impact, in the perspective of dense femto deployments. This is realized with a LTE coverage simulator that makes simple assumptions on the interference modeling and does not consider, in particular, inter-cell interference coordination. Simulations make profit of the path-loss models defined in [Freedom-D21] and enhanced in [Freedom-D31] to provide realistic SINR and throughput maps, then allowing the analysis of the femto interference versus a large number of parameters: FAP deployment scenario, FAP location inside the building, transmit power, traffic load, etc. The simulation methodology is detailed in section 3, supporting both the open- and closed-access modes. The results, given in section 8.1, may be viewed in two different ways: as a characterization of the useful and interference signal levels; but also as a pessimistic reference giving the network performance that would be obtained in absence of any specific interference mitigation technique. Six main scenarios have been investigated:

- Urban corporate FAP deployment within one floor, in presence of co-channel macro coverage;
- Urban corporate FAP deployment within one building, in presence of co-channel macro coverage;
- Urban corporate FAP deployment within a whole co-channel urban macro-cell;
- Suburban residential FAP deployment within a whole co-channel suburban macro-cell;
- Urban corporate FAP deployment within one floor, in absence of any co-channel macro coverage;
- Urban corporate FAP deployment within one building, in absence of any co-channel macro coverage.

Finally, the coverage simulations provide outcomes towards the engineering rules elaborated in activity 6A2 and towards the 2A3 business model analysis. For this later application, network capacity has been evaluated considering different traffic evolution scenarios (section 8.1).

2 SCENARIOS

The scenarios of interest for system simulations and relevant deployments are reported in synthesis in in this section for 5A2 tasks, with reference to 2D1 business and technical scenarios. The specificities of each individual 5A2 task are detailed later in the dedicated technical sections. Details about the scenarios not referred to a mapped deployment, such as the homogeneous or inhomogeneous multi-building used for system simulations can be found in the document [Freedom-D51], Section 5.1.1.

2.1 Business scenarios

[Freedom-D21] introduces three different business scenarios:

- BM1: Corporate customer in urban/dense urban area, with existing macrocell network but insufficient indoor coverage and capacity.
- BM2: Corporate customer in remote area, without macrocell network.
- BM3: Residential customer in urban/suburban area, with existing macrocell network but insufficient indoor coverage and capacity.

The 5A2 simulations aim at providing results to evaluate the service quality that is experienced by the end-users, considering:

- The above mentioned business scenarios,
- Different FAP and user deployments,
- Interference management techniques.

All three business scenarios are addressed in 5A2 activities; however they are not necessarily investigated with the same level of priority. In particular, the activity on interference analysis (Section 3) focuses on BM1, which is judged as the most challenging in terms of interference and of major interest for operational deployments.

2.2 Abstract models

In view of the three main problems addressed in activity 5A2, which can be summarized as

1. Clustering,
2. Interference planning,
3. Interference analysis,

The technical scenarios described in 2D1 will be addressed taking into account some realizations of particular interest. While the general set up of the residential/corporate environment are already detailed in 2D1, the peculiarities of 5D2 induce to some extensions.

Additionally to the scenario properties addressed in details in [Freedom-D51] regarding FAP penetration levels, FAP positioning (e.g., deep or light indoor) overall cell load and balance MUEs/FUEs, an additional issue addressed in the present activity is the traffic load in the network due to applications running on mobile terminals. Simulations include data packet generation, inclusion of overhead, ACK/NACK and retransmissions of packet to reproduce the complete flux of data from a terminal to the serving BS (MBS or FAP).

Scenarios described so far in 2D1 consider the FAP deployment on a physical interference perspective only. The problem addressed in 5A2 system-level simulations involves different components of the network to be taken in consideration, such as FAP gateway, IP gateway, RRM and control, from the point of view of clustering and of resources management at scheduler level.

Several aspects of interference relations among transmitters can be inferred by direct measurements at PHY level. A complementary approach will be devoted to identify possible range of values of characteristic parameters, such as for example pathlosses, which will be useful for the purposes of the activity, devised in 5A2 and related to deployment peculiarities (e.g., FAP installed in several buildings, geographic location, etc.).

In the first case, transmitters can perform either standard evaluations, such as SNR measurement, or by implementing targeted procedures (e.g. enable listening and identification phases for each FAP) to obtain a list of other transmitters and pathloss evaluation. Possible methods to address this task will be developed in another section of this document (see 4.1.2).

2.2.1 **Buildings deployment**

The basic parameters about the buildings deployment for residential suburban and corporate urban scenarios, are described in details in Section 5.2 of 2D1 [Freedom-D21]. Appropriate issues regarding the activity 5A2 have been included in that document.

The realistic building deployments are

- Residential suburban scenario (from [Freedom-D21]);
  Femtocell areas are dropped with a random uniform distribution subject to a minimum separation. The density of femtocells is a variable in the simulations. Each femtocell area has one FAP that is assumed active, i.e. there is at least one active call/service. Each femtocell area is modeled as a 2-D rectangular house plus a surrounding lot. FAPs are randomly dropped within each house. FUEs are randomly dropped within each house or outdoor in the surrounding lot. MUEs are dropped uniformly and randomly within the macrocell. It is possible that some MUEs are dropped within a FAP area. MUEs are assumed to be indoor or outdoor.

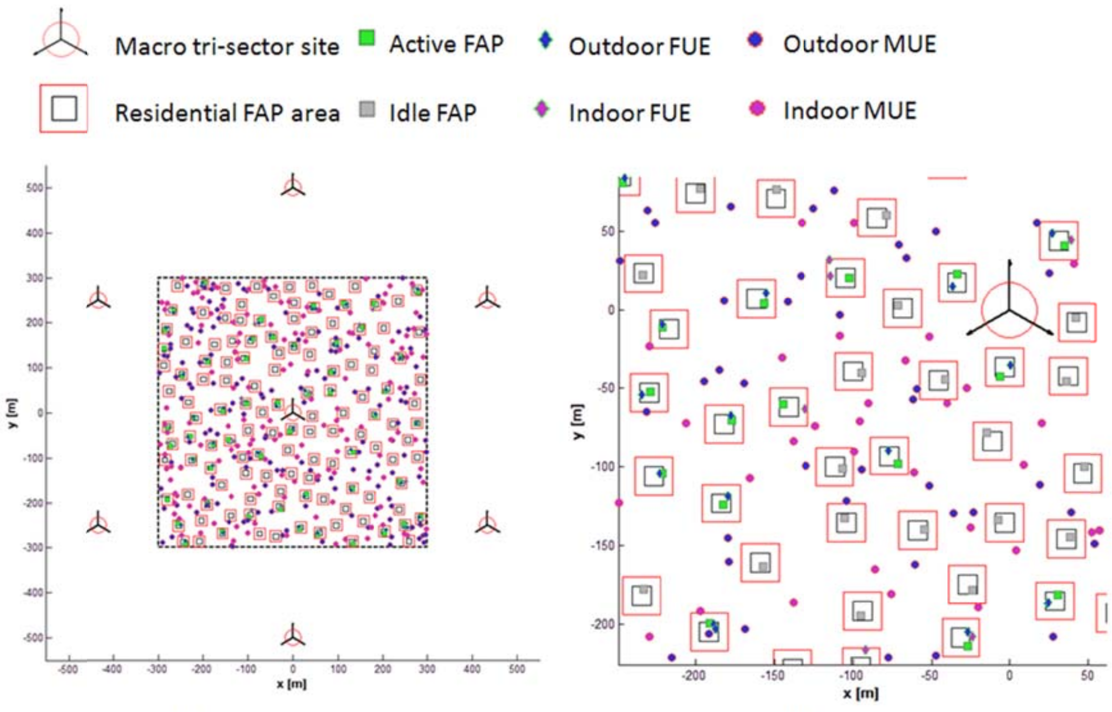
- Corporate urban scenario (from [Freedom-D21];
  Femtocells are deployed in urban building blocks, which are randomly dropped within the macrocell. Each femtocell block is represented by two stripes of offices separated by a street. Each femtocell block has *L* floors, where *L* is uniformly randomly distributed between 1 and 10.

- Inhomogeneous deployment: urban (used in clustering evaluation, i.e. devoted to investigate properties of several kinds of transmitters grouping in different ways);
  Femtocells are deployed in a strongly inhomogeneous scenario with four nearby building (4 to 8 floors) at the vertices of a square. Size of buildings and dimensions of the square and streets in between can be varied in the simulator. Deployment of femtocells is homogeneous within each building along floors and households. Part of MUEs is deployed indoor on different floors of the buildings and part is deployed homogeneously outdoor in the cell. FUEs are attached to FAPs indoor only. Number of FAPs, number of FUEs, number of MUEs (indoor and outdoor) are among simulation parameters.

2.2.2 **Distribution of users/femto**

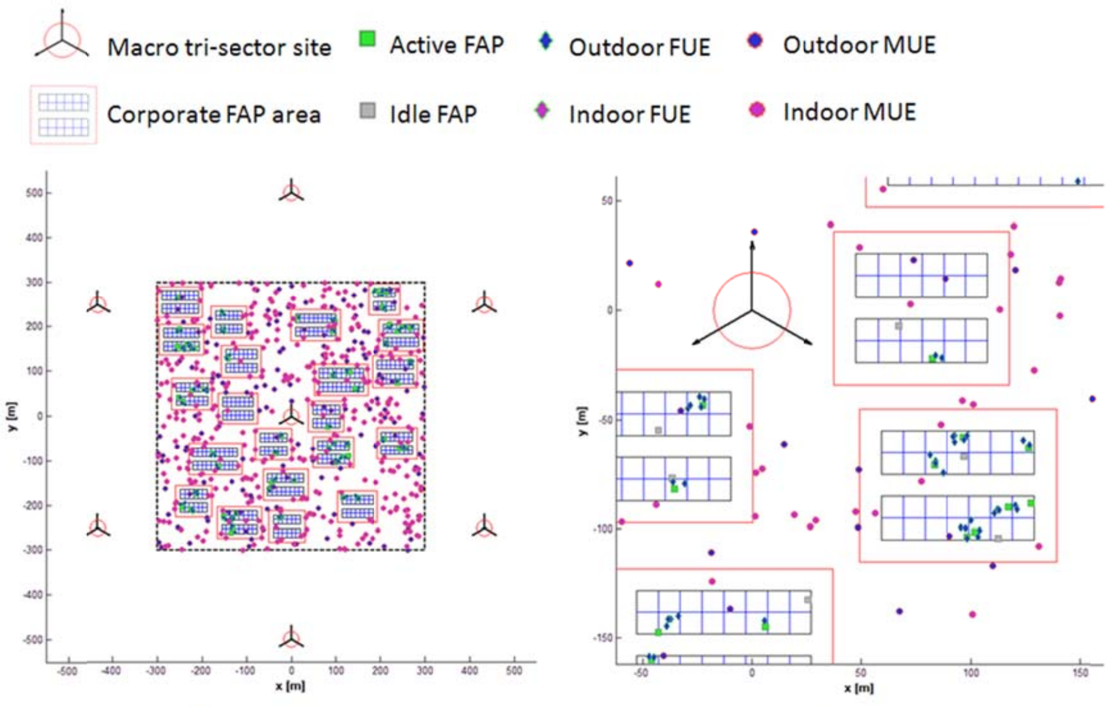
Rules for random users and femtocells distribution are described in [Freedom-D21]. A program is implemented in MatLab to automatically generate random building blocks, FAPs and UEs deployments. Figure 1 gives an example of residential deployment using the house model (i.e. 24m×24m FAP areas) and distribution rules defined in Table 17 of [Freedom-D21].

Figure 2 illustrates a corporate deployment using the two-buildings-stripe model and reference distribution values defined in Table 18 of [Freedom-D21]. For clarity, the figure shows only the elements at street-level or ground-floor level; however FAPs and UEs are distributed within all building floors. The deployments are generated within the central cells of a macro network with 500m inter-site distance.



(a) General view (b) Zoom view

Figure 1: Example of a residential deployment; only active FAPs are displayed in the general view (a); All active and inactive FAPs are displayed in the zoom view (b).



(a) General view (b) Zoom view

Figure 2: Example of a corporate deployment; only active FAPs are displayed in the general view (a); All active and inactive FAPs are displayed in the zoom view (b).

Focusing on the effect of the number of transmitters in a single building, a parameter has been introduced, representing penetration of FAPs adoption in a certain area, given by the percentage of households with a couple FUE/FAP inside. The density of users/femtos couples in the households/offices varies from 0.125 to 1 FAP (unity holds when each household has an active FAP). The effective deployment will take also in consideration inhomogeneous distribution of transmitters, specifically to test different clustering strategies. This is a macro-parameter of interest when considering strategies to mitigate or coordinate interference.

	FAP density			
	N FAPs			
		8	***16***	***32***
N Floors	***2***	0.25	0.5	1
	3	0.17	0.3	0.7
	4	0.125	0.25	0.5

Table 1. FAPs density inside a single building.

2.3 Deployment complexity

The analysis of network activity is focused to address scalable algorithms and the scenarios considered will have increased complexity, as number and dimensions of floors and number of buildings.

2.3.1 **One building, single floor**

Clustering methods will be first analyzed in a simple, one floor building, resembling a corporate scenario. Indoor propagation effects are considered for grouping users to test the benefits of optimization strategies.

2.3.2 **One building, multiple floors**

Similarly to the case of single floor, clustering property emerges with more clarity when increasing the number of floors in a building, leading to a partition criterion based on interference among transmitters.

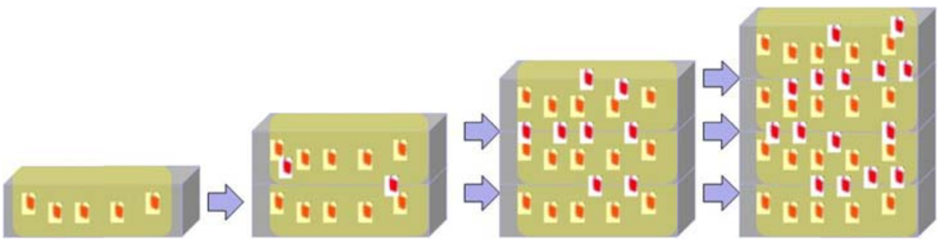


Figure 3. Scheme for increasing buildings structure complexity

2.3.3 **Multiple buildings**

Activity 5A2 will investigate additional deployments to determine if and how the simulation results depend on the building block model. The obtained results will be compared to simulations adopting parameter from real environments, such as adopting the propagation properties provided by VolcanoLab.

- Considering that adjacent offices belong to the same corporate unit, then FUEs are not necessarily in the same office as FAPs;
- Considering that adjacent buildings belong to the same corporate unit, then FUEs are not necessarily in the same building as FAPs; see different corporate scenarios that may be explored in Figure 4.

- Or working with real environments, where the building model is a precise representation of an existing urban area (precise building contour and height); see details in section 2.4.

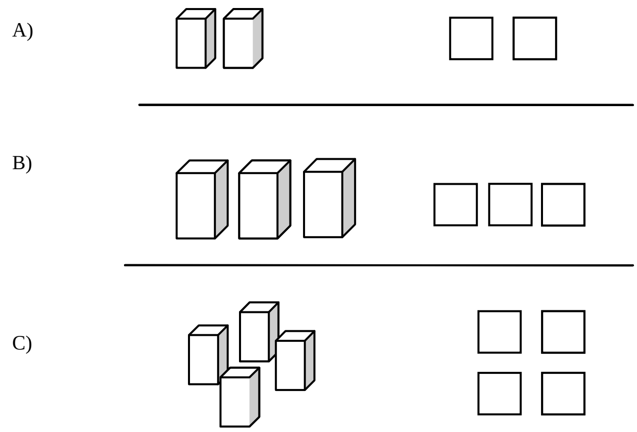


Figure 4. Scheme of several buildings deployments and patterns. Left side of figures represent possible deployments of buildings, right side represents the scheme on ground. Interference among transmitters deployed in different buildings is coherent with clustering criteria.

In view of analyzing network and interference properties for a strongly inhomogeneous distribution of FUEs/FAPs, a major focus has been given to a deployment with four buildings. In the cell area, MUEs are uniformly deployed both outdoor and within each single building, FUEs and FAPs are deployed only indoor. An algorithm to deploy a variable number (e.g., 10 to 800) of MUE, FUE, FAPs has been implemented, allowing to modify a set of parameters which have been considered of interest for this task, i.e.:

- Size of building (width, length, number of floors, ceiling height, size of street in between);
- Number of MUEs indoor, MUEs outdoor, FAPs, maximum distance FAP/FUE.

The effects of interference can for example be addressed in the case of MUEs outdoor only, or for a varying number of MUEs also indoor. This allows testing macro/femto-network resources allocation in different conditions. Figure 5 reports a visualization of a possible deployment.

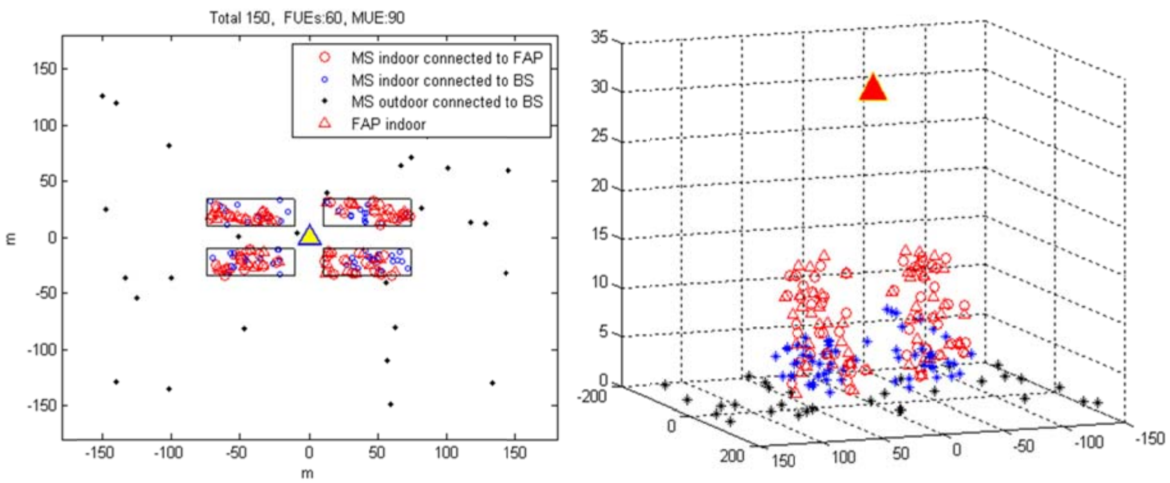


Figure 5: Example of an inhomogeneous deployment. Left: highlight of 4 buildings. Right: 3D view of the same distribution. Black and blue stars represent MUEs outdoor/indoor, respectively; in red, circles represent FUEs, triangles FAPs

2.4 *Realistic deployment models*

Even more realistic deployments may be obtained by the association of:

- Real description of the environment, also called geographical map data.
- Site-specific path-loss models defined in [Freedom-D21] and enhanced in [Freedom-D31]. The path-loss models simulate physical interaction between the propagation wave and the propagation environment (diffraction on building tops, reflection on building façades, etc), then predict part of the path-loss shadowing.
- Realistic MBS, FAP, UE and FUE deployments, based on an analysis of the geographical map data, and depending on the FAP density and FUE density.

The objective of running scenarios based on this realistic deployment and environment representation is twofold:

- To get additional simulation results about interference in scenarios very close to reality;
- To compare results obtained from theoretical and generic deployments to those obtained from realistic but specific deployments; in particular, we can verify if conclusions obtained from a realistic deployment were also caught from analysis of theoretical scenarios.

Realistic scenarios will be also simulated from the introduction of a shadowing component depending on the density of human activity, as proposed in [Freedom-D31].

2.4.1 **Geographical map data**

Geographical map data used in FREEDOM simulations will be composed of three different layers:

- Outdoor 3D building layout;
- Terrain altitude;
- Indoor partitions (optional).

Figure 6 gives an example of outdoor representation in a European city and Figure 7 illustrates the indoor representation of a real corporate building.

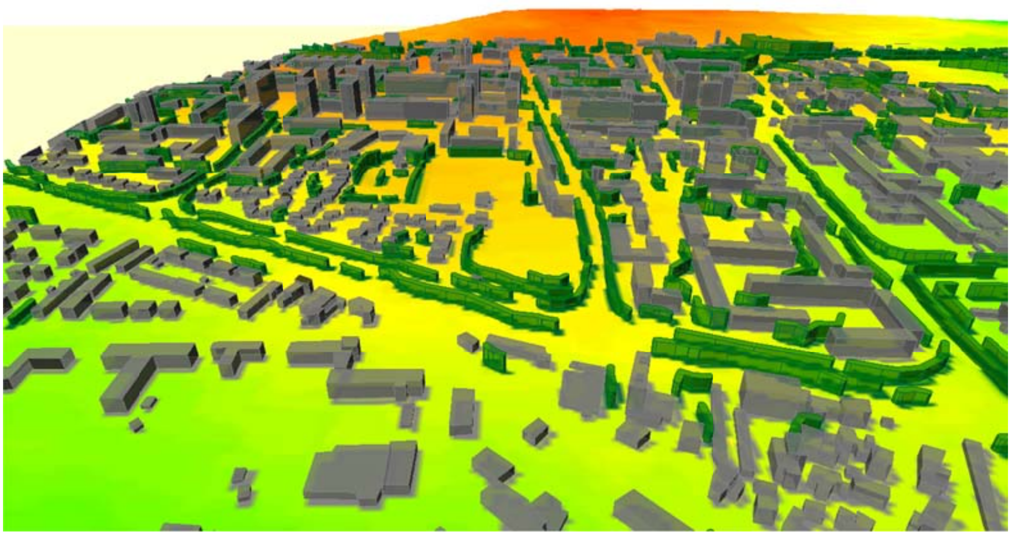


Figure 6: 3D outdoor building layout and terrain altitude.

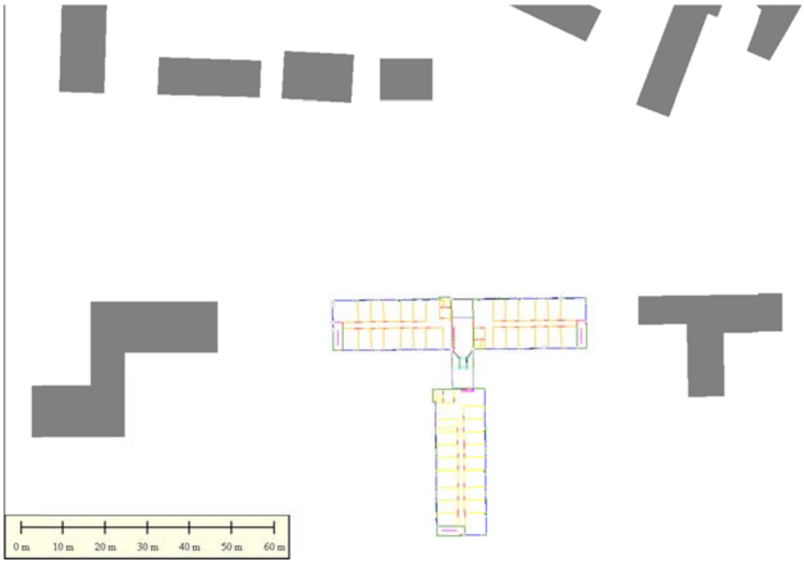


Figure 7: Indoor partition inside a real corporate building with surrounding buildings (top view).

2.4.2 Distribution of macro-BS/users/femtos

MBSs are "manually" distributed in the simulation environment to achieve a target mean throughput at the cell edge. This cannot be done from a fixed inter-site distance, as the coverage range of each MBS is a function of the surrounding environment (terrain variations, buildings).

Macro users are randomly and uniformly distributed in the horizontal plane, as for theoretical deployment scenarios. Indoor users are then uniformly distributed in the different building floors, taking into account the real building height provided by the geographical map data.

As well, the FAPs are randomly distributed in the horizontal plane (provided they drop inside a building) but with a probability that depends on the building height (meaning that the probability that a FAP drops inside the horizontal contour of a 4-floor building is twice the probability it drops inside the horizontal contour of a 2-floor building). Then FAPs are uniformly distributed in the different building floors, with a constraint on the minimum distance between two FAPs at the same floor. Remark that all rules for this FAP distribution are not yet defined and will be derived during the 5A2 activity.

Finally, the FUEs are uniformly distributed within building contours, at the FAP floor, and with a constraint on the FAP – FUE distance. Here also, the precise distribution rules have to be decided.

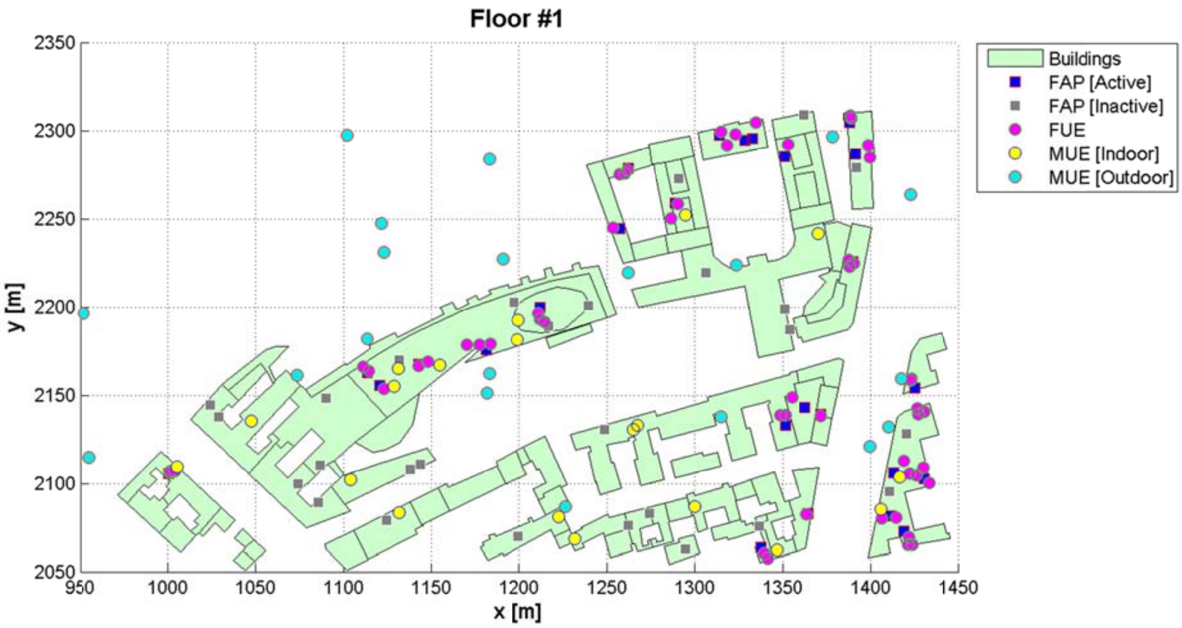


Figure 8: Example of a urban corporate deployment; For clarity, only deployment in the building first floor is displayed.

3 INTERFERENCE ANALYSIS

This section describes the simulation tools and methodology that are elaborated for analysis of the femto-based interference, in the perspective of dense femto deployments. This analysis does not rely on system-level simulation, but on coverage predictions making some simple assumptions on the interference modeling. The conclusions of this analysis should be used as a reference in the evaluation of the interference mitigation techniques (based on system-level simulation) and elaboration of the business models.

3.1 System assumptions

LTE system operating around the frequency 2.0 GHz is considered. The coverage simulations studied in this section do not consider any particular scheduling or resource allocation algorithm. They rely on the calculation of an effective signal to interference plus noise ratio (SINR) that fully abstracts the impact of the MAC layer protocols and resource allocation. The key parameters for MBS, FAP and UE are the ones provided in Tables 13, 14, and 15 of [Freedom-D21].

3.2 LTE coverage simulation

The simulation basically relies on the calculation of the effective signal to interference plus noise ratio (SINR) on downlink (DL) which is calculated over a 3D pixel grid that represents all possible locations of the User Equipment (UE), i.e. the 2D pixel grid that is usually computed in coverage analysis is extended to multiple floor reception heights. This effective DL SINR does not result from simulation of any particular scheduling or resource allocation scheme, but rely on a simple abstraction of the MAC layer protocols, where the total power received from an interfering cell is given by the maximum transmit power times the channel path-loss (including antenna radiation gains) and a DL traffic load (TL). This TL in the range from 0 to 100% represents the average portion of signal resources that are allocated to the cell users. The MAC layer abstraction does not consider any interference mitigation technique, thus the set of resources allocated by each cell is viewed as random and independent. Finally, the available spectral efficiency is given by a SINR mapping table [Mehlführer09]. Remark that multi-antennas are employed here only for diversity gain, thus throughput enhancement from spatial multiplexing is not considered.

The LTE coverage simulator is adapted to femtocell deployment by introducing active and idle FAP's in the network description, defining the access mode of each FAP, and adding the concept of UE femto-profiles:

- No-FAP subscriber: UE may be served by any MBS or FAP in open access mode.
- FAP-subscriber: UE may be served by any MBS or FAP in open access mode, as well as the neighbor FAP when the UE is located in a FAP area (assuming that the UE is part of the CSG of this FAP).

The LTE coverage simulator predicts service coverage and spectral-efficiency maps for one specific UE femto-profile. In that way, the simulation provides a result that would experiences either a macro user or a femto subscriber.

The coverage simulation requires a 3D path-loss map around each MBS and FAP (instead of a 2D map generally used in this kind of tool). It is composed of:

- One outdoor-layer (or pixel grid) for path-loss between MBS/FAP to outdoor UE.
- Several indoor-layers (or pixel grids) for path-loss between MBS/FAP to indoor UE at different floor heights.

The mean path-loss and shadowing component are provided either by the analytical models (for theoretical deployment scenarios) or site-specific models (for realistic deployment scenarios) defined in [Freedom-D21] and [Freedom-D31].

3.3 Simulation workflow and Performance analysis

The simulation workflow is divided in the three successive steps illustrated in Figure 9. The first step defines the network topology. The macro layout is fixed, organized as two rings around a central three-sector site, as shown in Figure 10. The FAPs are randomly deployed into buildings within the three central cells.

In studies based on a synthetic environment (i.e. buildings are represented by rectangular blocks separated by a 20m wide street), the buildings are randomly dropped in the study area. In study based on a real environment, a 3D geographical map data is used. Corporate buildings where FAPs are installed are randomly selected among the buildings located in the study area, using an average corporate building ratio. In both cases, buildings are divided in 100m² small areas, where at most one FAP is authorized to be installed. Then small areas with a FAP are randomly selected depending on a FAP density, i.e. percentage of small areas owning a FAP. Finally, the location of the FAP within the small area is generated from a random distribution law. A FAP is not necessarily active, meaning that there may be no user in communication with this FAP, except the user for which the coverage is simulated. The activation of a FAP is random, based on an average activation ratio in range from 0 to 100%.

Coverage is simulated in the second step from respectively the macro-only and random two-tier networks. Outputs are 3D maps providing the service coverage area, the best-server and the available spectral efficiency at any possible UE location in the streets or in building floors. Two different FAP access modes are simulated: open or closed. In case of the closed access mode, two different types of user are simulated: FAP subscriber or non-subscriber.

This simulation step includes a part of randomness, as a spatially-correlated lognormal shadowing term is added to the predicted mean path-loss. This lognormal term actually represents the unpredicted or mis-predicted part of the shadowing. This is an alternative to the error margin that is usually accounted in the radio planning simulation methodology. It permits a more realistic evaluation of the network performance evolution from the macro-only to the two-tier network topology, however at the expense of a time costly Monte-Carlo computation (composed of N random realizations as shown in Figure 9).

The third step provides statistics on the coverage simulation outputs, and in particular compares the coverage performance in the macro-only and two-tier networks.

Remark the second step (coverage simulation) is implemented in the VolcanoLAB platform, while the generation of the network topology and the LTE output processing are run in MatLab. This workflow has been facilitated by the development of VolcanoLAB-Matlab interface features that allows the simulation chain to be mostly automatic.

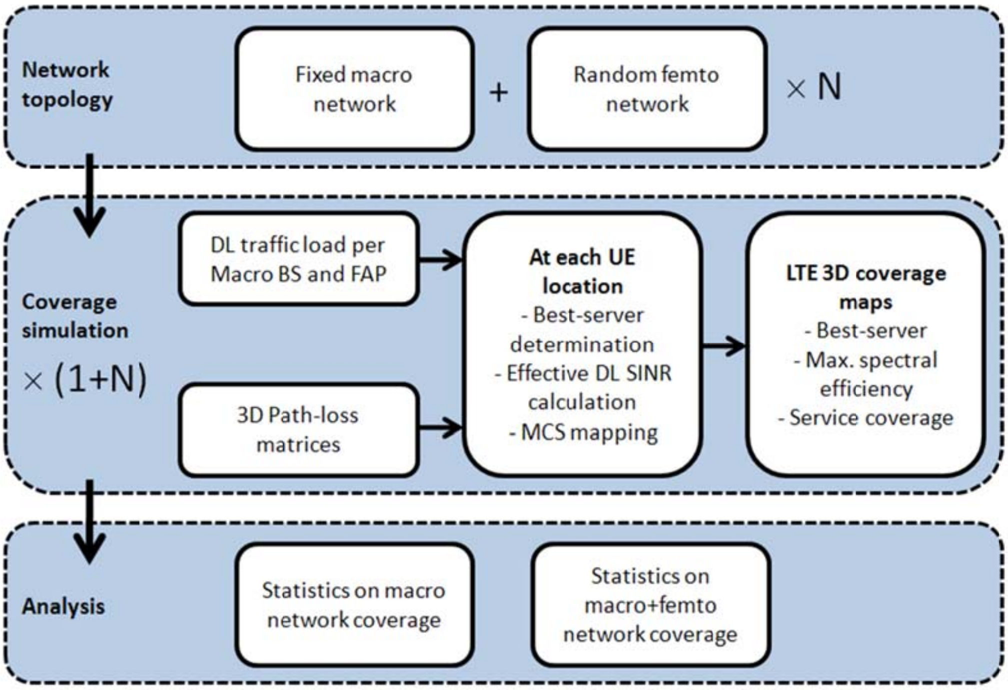


Figure 9: Outline of the simulation and analyse procedure.

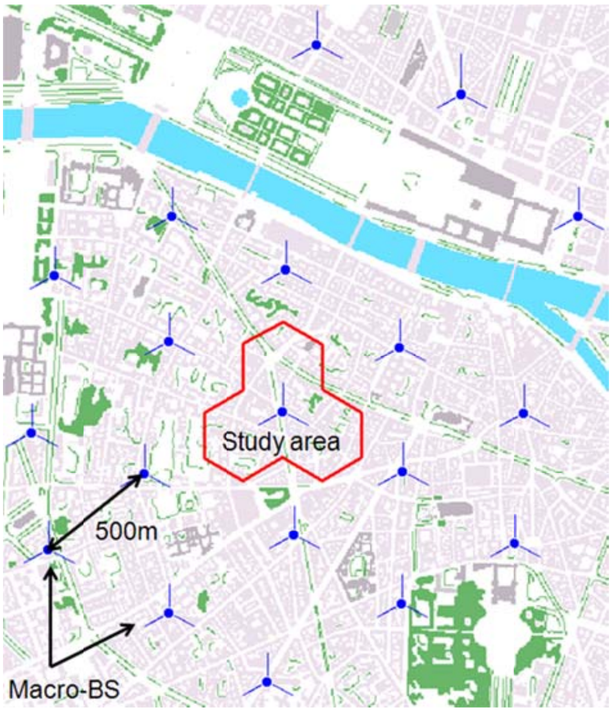


Figure 10: Macro layout and study area in a real environment.

3.4 Identification of femto-based interference impact

The impact of femtocell deployments in terms of interference but also coverage and capacity enhancement is characterized by comparison of the simulation outputs: comparison between macro-only outputs, femto-only outputs and macro+femto outputs. This impact is studied as a function of the FAP density into the network, FAP density into a building floor, FAP transmit power, FAP access mode, FAP location into the building (random, close to window, regular deployment, etc.), FAP distance to MBS, MUE distance to FAP (inside same FAP area, inside same floor, …) and network traffic load. Several inter-site distances are simulated to address both noise-limited and interference-limited macro networks.

Co-channel macro and femtocell layers are considered. Highest priority is given to the investigation of the DL femto-to-macro interference in urban area. This is expected to be the most critical issue, where a dense femto deployment can significantly degrade the macro-layer coverage.

Six distinct simulation scenarios have been designed so far, based on DL network coverage, and covering all 3 FREEDOM business scenarios:

- Scenario IA-1: Evaluating the local impact of a single-floor corporate FAP deployment in an urban macro-cell (addressing BM1).
- Scenario IA-2: Evaluating the local impact of a multi-floor corporate FAP deployment in an urban macro-cell (addressing BM1).
- Scenario IA-3: Evaluating the impact of a dense corporate FAP deployment on the coverage quality of an urban network (addressing BM1).
- Scenario IA-4: Evaluating the impact of a dense residential FAP deployment on the coverage quality of a suburban network (addressing BM3).
- Scenario IA-5: Evaluating the local impact of a single-floor corporate FAP deployment in absence of macro-cell signal (addressing BM2).
- Scenario IA-6: Evaluating the local impact of a dense corporate FAP deployment in absence of of macro-cell signal (addressing BM2).

Results are given in section 8.1.

4 INTERFERENCE PLANNING

4.1 Clustering metrics

The problem of clustering in a telecommunication network is treated considering several clustering distances, classified on the basis of their nature: it can be a proper geographical distance with respect to the corresponding interference and pathloss or otherwise an abstract distance, as for example in the case of type or properties of service applications running on the terminals.

4.1.1 Geographical deployment

The network infrastructure provides different ways to assess if and how the FAPs are installed in a building or in another. Depending on the method used, the system can evaluate the interference structure for the FAP tier with varying levels of accuracy. Of course, the accuracy about the geolocation of a FAP/FUE, comes from the localization capabilities of the single devices:

- Triangulation towards surrounding BSs (whose positions are known with an accuracy of order of 1 m) thus allowing an accuracy of order of tens of meters; this method requires a dedicated software and needs to be run only once, when installing the single FAP, or eventually at start-up. For actual smartphones it is a built-in operation.
- GPS positioning which, together with assisted GPS, can provide accuracy to the order of few meters requires a dedicated hardware and, although not included in some of the FAP devices already on the market, is planned for some advanced models and for next commercial generation. This is present on most smarthpones in the market.
- An approximate estimate comes from the IP number assigned to single FAPs. From the known structure of the subnetwork the system can exclude or include a FAP from a cluster;
- A different (although still raw) estimate comes from the knowledge of the femto-gateway of reference, whose accuracy comes from the deployment choices: it could be to building or to floor level, depending on the cabling of the building. For the actual business models, this is an operator choice.

Although the positioning through triangulation or GPS requires devoted hardware (GPS chip) or operations (signal processing) which could not be already implemented in all femtos in the market, the FAPs can anyway obtain the positioning information from the companion mobile terminal. The accuracy required for clustering is within the range of a FUE with its FAP.

4.1.2 Interference relation

From the system’s perspective, interference among transmitters is described in terms of pathloss, whereas is described in terms of SNR from the point of view of the units deployed in the cell. Of course, pathloss by itself is not exhaustive unless including transmitting power and band assignment to evaluate SNR. Different strategies for the allocation of the resources can provide different performances in terms of throughput, call drops, change of MCS (affecting energy consumption).

4.1.2.1 *Pathloss*

The evaluation of pathloss among transmitters has been considered from different perspectives, depending on the performed system analysis: the following case 1 is focused on small scale clustering and optimization of resources allocation; case 2 considers the whole network, including macro BS and an arbitrary number of MUEs.

Case 1 is considered for the optimization of transmission resources among one set or several sets of users, as for example FAPs in a single building, thus the abstraction has been limited to consider a pathloss matrix, summarizing the pathloss among the set of FAPs (e.g., labeling rows) and the set of FUEs (labeling columns).

Case 2 outlooks the whole cell, thus, due to its complexity, further details will be provided in the second part of current Section.

Case 1

The analysis of the pathloss matrix, providing the pathloss relation among all transmitters in the network, provide a method to group users on the basis of their capability to interfere each other and for transmitting with their intended counterpart (i.e., FAP-FUE or FUE-FAP).

Since it is natural that a physical deployment of transmitters provides a scenario in which not all transmitters have appreciable interference from all others, several realistic cases are considered in relation to explicit scenarios, which allow inferring a clustered structure.

We will address several methods to provide an estimate or a measurement of the pathloss matrix, i.e. a matrix with a number of rows (columns) corresponding to the index of MUEs (FAPs) whose elements are the relative pathlosses (e.g. in dB). Elements on the diagonal represent the pathloss of the signal from the transmitter to the intended receiver, off-diagonal elements represent the loss of power for the interfering components. For example, a computation *ab initio* shows that, for a regular type of building with several floors (the approach has been tested from 2 to 5 floors), the pathloss matrix shows a peculiar pattern with squares reflecting the floors distribution, as is visible in Figure 11.

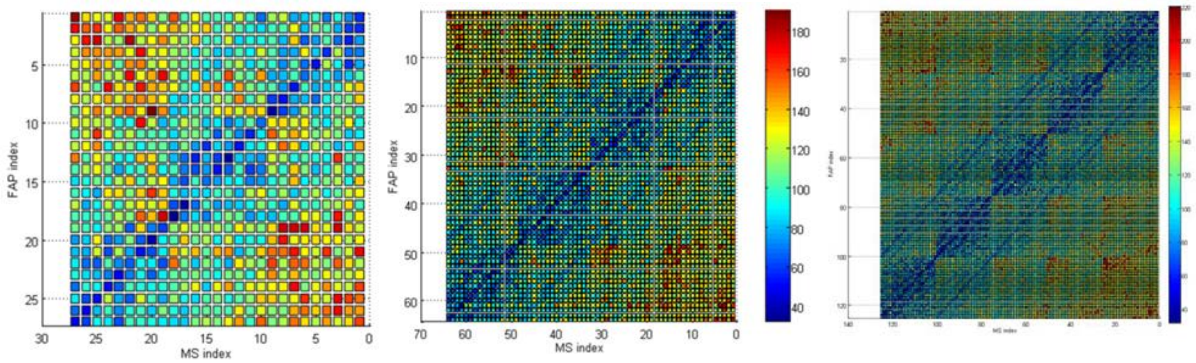


Figure 11. Examples of pathloss distribution, in dB, for a single building with different number of floors: left, 27 FAPs, 3 floors; center, 64 FAPs, 3 floors ; right, 125 FAPs, 5 floors.

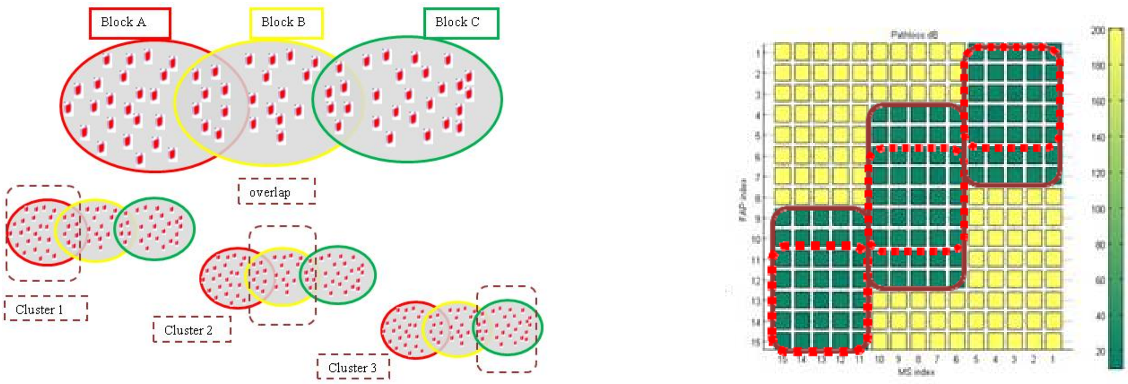


Figure 12. Example of pathloss distribution, in dB, for 3 nearby buildings, assuming a homogeneous FAPs distribution within each one.

Another situation is represented by the deployment of FAPs in nearby buildings, as depicted in left panel of Figure 12. The colored circles group FAPs in a specific building, and every set has an intersection with nearby sets. From the pathloss matrix, represented in the right panel of Figure 12, each vertical rectangle in dashed line represents a cluster. This example is designed such that 2 transmitters overlap with those nearby buildings, thus 2 from the left-most and 2 form the right-most buildings interfere with all from the central building, and 2 couples from the central interfere with all from those on the sides. Such a situation is indeed very common.

Case 2

Considering a single cell, a geographical deployment of transmitters is given. A software has been developed to compute pathloss and SNR sensed by all transmitters. The simulator emulates the capability of single transmitters to evaluate pathloss with respect to all other transmitters in range and provide the sensed SNR at each simulation time epoch. Although in a static scenario pathloss can be assumed constant, the instantaneous SNR depends on the sequence of single transmissions. Since the time grid of events allocations is at the ms scale (in compliance with the LTE frame structure) the temporal variation of the SNR has a complex varying texture on the same time scale. Eventually, the macro network can be temporally independent from the femto-network, as synchronization among the two tiers could be implemented or not, depending on operators network design and can be dropped in the adopted scheme. Synchronization at system level and implications have been extensively discussed and evaluated in Section 6.1.3 of [Freedom-D51].

Indeed, synchronization is a very demanding task whose complexity and cost in terms of methods and resources appears unlikely in the addressed scenarios and use cases. If the operator implements a synchronization method, the clustering procedures are speed up. Let us briefly examine the two possible synchronization cases: BS/femto-network and FAP/FAP.

- Synchronization BS/femto-network. This can be either through the radio link, or the backhaul. In the first case, one has to suppose that the BS is in range and the signal has a sufficient quality to decode pilot symbols or preambles to perform synchronization process up to order of few ns. This is not the case when the FAPs are deployed in absence of macro BS or when the BS signal has very bad quality. In fact, if the signal of the BS would be good, the FUE would be unlikely to register to the FAP, unless some other mechanism would be implemented (e.g., always register to the FAP, when in range). Synchronization through the backhaul link would depend on a signal sent through the IP network, but this would be affected by an arbitrary random varying delay which would not be controlled by the femto processing.
- Synchronization FAP/FAP. For this case the same considerations exposed for the last case apply, worsened by considering that when FAPs are distributed, the radio link among them deteriorates even faster that the link to the BS.

The system simulator evaluates pathloss relations following the propagation models detailed in 2D1 for each transmitting unit with respect to all others:

- Between BS and MUEs, FUEs, FAPs;
- Between MUEs and FUEs;
- Between FAPs and FUEs, MUEs.

From an operational point of view, this could be achieved by supposing that each unit performs a periodic (for example, at start-up and at the minutes time-scale) sensing of the surrounding environment, based on preambles or pilot symbols with known power values.

4.1.2.2 ***SINR***

The system simulator implemented by DUN reproduces the sequence of transmission events in agreement with the LTE frame structure (refer to sections 6.2.1 and 6.2.2 for some technical details and to Section 5 of [Freedom-D51] for a detailed description of the transmission events processing). At each time epoch, the simulator reproduces to millisecond scale the activity of transmitters in the network, thus providing the instantaneous SINR for every unit due to all transmitters in range.

For each receiver, DL/UL subframes are in an ordered sequence. The texture for the macro-network regards all MUEs, while the femto-network can be more complex as each FAP has an independent traffic scheduler and thus DL/UL phases could be inverted with respect to other FAPs. The implemented time grid can picked from those reported in Table 2 on p. 49, which are related to specific requirements of the access point. For example, a FAP handling VoIP applications only could apply a scheduler with an even sharing of UL/DL transmission opportunities; in the case of video-streaming applications, it could adopt an sharing with more room for the DL phase to cope with a higher DL data flow. Alternatively, the choice could be also driven by the number of active FUEs registered to that FAP, each requiring a different type of service and thus assigning more time slots to the UL.

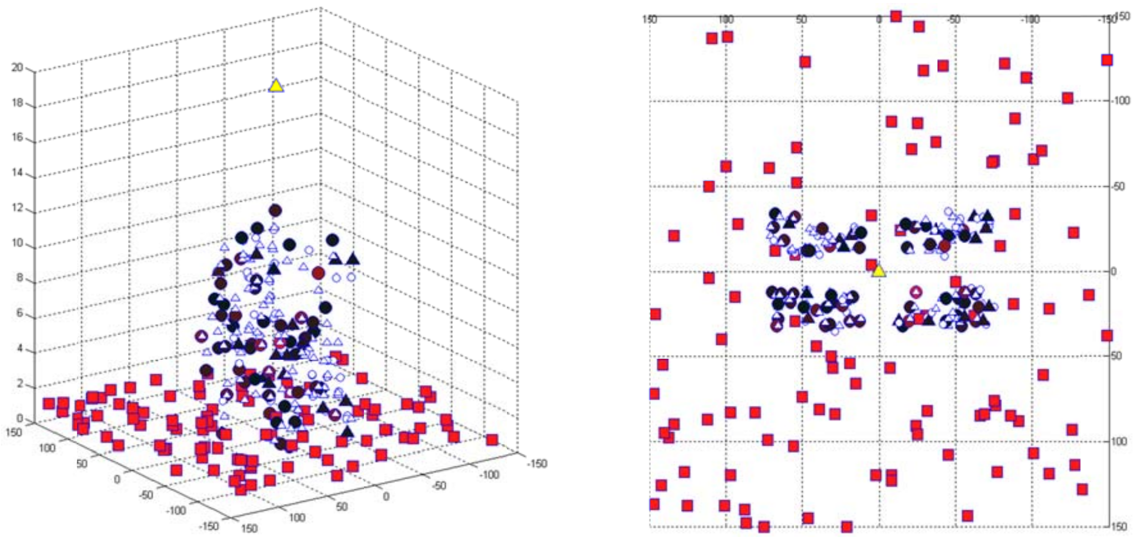


Figure 13. Example of an inhomogeneous deployment of 100 couples FAPs (triangles) /FUEs(circles) distributed in 4 nearby buildings and 100 MUEs (squares) outdoor. Yellow triangle represents the BS. Filled symbols represent receiving units, empty symbols transmitting ones: in this timeshot MBS is in DL.

The temporal evolution of the SINR depends on the instantaneous DL/UL activity of all users. The graphics in Figure 13 and Figure 14 represent two instants of time (one millisecond subframe) for an inhomogeneous deployment of FAPs in four adjacent buildings. Filled markers represent receiving units and MUEs are mainly outdoor: in Figure 13 MUEs (squares) are receiving (BS is in DL) while some FAPs are receiving and some others are transmitting. In Figure 14, all MUEs are transmitting (MBS in UL) and the FAP network is still in a composite activity. The evaluated SINR is a varying quantity whose fast temporal behavior is evaluated at system level. The average value of such SINR can be adopted as a slowly varying metric describing system (or of a part of it) properties.

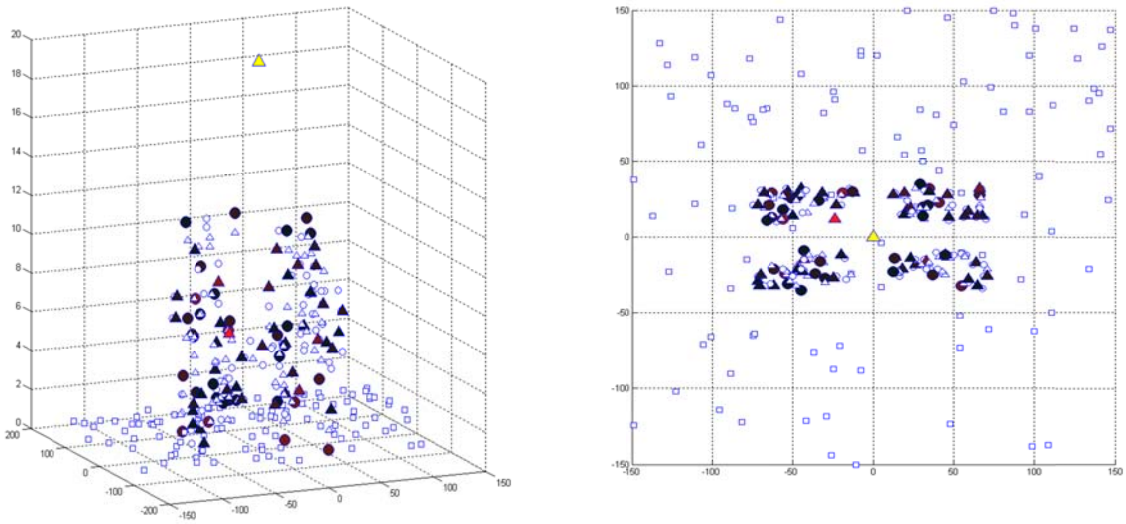


Figure 14. Same as in Figure 13, macro network in UL.

4.1.2.3 *Methods for evaluating presence and relation to other transmitters*

The possible methods to estimate pathlosses and SINRs are analyzed here. To obtain the list of other transmitters in range of the MS (or FAP) different strategies can be implemented, either passive or active.

A passive method is that a unit could periodically listen to the transmissions of other units and keep track of their APN Identifiers (SSIDs) and/or IDs. Eventually, the list of all transmitters in the area and/or the available parameters characterizing their transmissions could be broadcasted via IP through the backhaul channel to a set of FAPs/FUEs/MUEs that can be interested. This choice must be devised as the network administration model. Moreover, the collection of the IDs can be performed in a distributed of centralized way, depending on the flux of information strategy adopted.

An active method to measure relative SNRs and/or pathlosses requires the implementation of some tasks periodically performed by the FAPs/FUEs. This requires the allocation of dedicated listening time slots devoted to decode specific signals periodically transmitted by other users, which could be standard pilot signals or frame prefix, such as for example Frame Preambles or, eventually, partial negotiations of service. More actively, the system could implement a method for signaling among a selected set of transmitters in range to exchange some basic negotiation information in order to have an estimate of PL between each couple of transmitters in range. This would be a slowly varying parameter for indoor users: FAPs are assumed static, FUE can move only in the range of few meters at very low speeds and activity of MUE is limited since either have a limited range (if located indoor) or have a transient effect when passing by (if located outdoor). Tables of users in range can be broadcasted and periodically updated, although one could expect that significant changes happen sporadically only and would be slightly more frequent for the corporate scenario. Indeed, in the urban deployment FAPs are placed in households and the number and ID of users can change only when a guest camps on the femto and gains access to it. On the other hand, for the corporate scenario the mobility of users can be more significant, e.g. a FUE passing from one area to another of the corporate, and similarly the number of guests can be more significant and vary from day to day.

4.1.3 **Priority of user/service**

An interference management strategy, focused also on the effective traffic properties (requested or granted), can deal also with the identification of clusters (in this case, intended as “groups”) of users on the basis of the type of priority in relation to the service running on the mobile device. In this sense, we can for example distinguish among voice, web browsing, video streaming and so on. Priority for an operator would focus on guaranteeing QoS first on basic services, than on delay tolerant applications.

Similarly, resources allocation can rely on the type of service requested by a terminal, such that an optimization strategy can assign priority of a service (e.g., voice) with respect to others. An overall fairness criterion can depend on the quantity of services running on each terminal and on the requirements that such services have to run.

4.1.3.1 *Type of service*

Simulations will consider VoIP, web browsing, streaming as the main types of service to simulate. Different types of data flux can be represented as FTP or video/audio streaming by tuning parameters of generation (e.g., average packets dimensions depending on coding, interarrival time) which are proper of the specific application and can be considered more or less relevant applications with respect to others, in view of the different requirements on latency.

4.1.3.2 *Traffic load/QoS*

Different services can be grouped on the basis of traffic load and/or QoS to run. A fairness policy could consider this characteristic as a reference, thus leading to a different fairness criterion.

4.1.3.3 *Latency*

Some services are not delay-tolerant and pose the most stringent requirements on packet queues. Evaluation of backhaul quality will be considered for its impact on packets delay and jitter affecting IP traffic from the FAPs, providing input to the business model treated in WP2. This aspect can be dealt at radio level (considering link quality improvement) or at scheduler level, assigning more time slots for transmission to impaired users with longer queues to digest.

4.1.4 Interference based on users activity

Different activity profiles can be defined from a selection of characteristics above mentioned: for example, a type of activity can be a high latency tolerant application with high traffic load (e.g., ftp).

4.2 Clustering at system level

The mentioned distances and the related metrics can be treated at a local or at centralized level, as well as with different levels of hierarchy. In fact, a distributed algorithm can be locally run to identify a set of transmitters interfering each other in view of feeding back to the RRM a slowly varying metric describing an aggregate measure of the transmission properties characterizing such local cluster. This is provided by:

- Overall capacity/throughput of the local cluster
- Distribution of throughput among transmitters belonging to such cluster
- Distribution of SINRs among such transmitters
- Fairness of the resources allocation
- Number of disconnections.

The possible metrics will allow the comparison among different solutions, thus considering the benefits of the clustering strategy on the overall network.

4.2.1 FAPs clustering

Given a deployment of N FAPs, the system can be represented as p clusters $\Lambda_1, \ldots, \Lambda_n$. Each cluster Λ_a, $a=1,\ldots,p$, is a set of FAPs including λ_a FAPs each, so that $\sum_{a=1}^{p} \lambda_a \geq N$, since it can also be verified that $\Lambda_a \cap \Lambda_b \neq \emptyset$, i.e. a single transmitter can be included in two separate clusters. Labeling the FAPs by ε_j, $j=1,\ldots,N$, the overlap between any two clusters composed as

$$\Lambda_{n1}=\{\varepsilon_1, \ldots, \varepsilon_s\}, \quad \Lambda_{n2}=\{\varepsilon_{s-r}, \varepsilon_{s-r+1}, \ldots, \varepsilon_t\} \qquad t>s ,$$

is measured by r when r FAPs belong to both sets.

In view of large population deployments, the algorithm scalability performances have been introduced and tested for the Genetic Optimization (GO) algorithm developed in WP3, outlining some methods to reduce its complexity from the whole set of FAPs to every single Λ_a.

Based on the criteria mentioned in section 4.1 (and its subsections), a formalism to describe clusters of users can be introduced. For the sake of clarity, we will use as a reference example to describe the analysis the criterion based on the pathloss matrix. When a FAP can be assigned to a sub-set, the task is to reduce the whole set into p sub-sets Λ_a ($a=1,\ldots,p$), interpreted as clusters. An example is given by the FAPs deployed in two nearby buildings, B_1, B_2 (for simplicity, $p=2$): suppose that s_1 FAPs are in building B_1 and s_2 in B_2. A portion r_1 of s_1 interferes also with r_2 of s_2. The cluster Λ_1 is constituted by r_2+s_1 FAPs and the cluster Λ_2 is given by r_1+s_2 FAPs.

The physical characteristics of the deployment can be reflected by the structure of the pathloss matrix: the interference among FAPs within the same building (e.g., s_1 or s_2) is dominant while some of them (r_1 and r_2, respectively) interfere also with some FAPs in the building nearby.

Thus, in case an optimization process is implemented, either the entire set of FAPs is forwarded to the GO or it is split into p sub-sets that are processed in parallel. The adoption of a clustering criterion is an advantage if the system, in terms of pathloss distribution, can be split into sub-systems for which the border effects, quantified by r_1 and r_2, are computationally feasible such that $r_a < s_a \; \forall a=1,\ldots,p$, i.e. if the number of FAPs belonging to both clusters is less the number of FAPs belonging to a single cluster. If this is not verified, the system is not reduced to a set of sub-systems whose management implies less complexity than the management of the whole system at once.

Dealing with border effects is a focal point to express the efficiency of the parallelization algorithm. For the sake of clarity, we specify the meaning of the terms adopted for treating the scalability issues:

- **Blocks**: FAPs grouped in terms of their geographical location, e.g., those within the same building. Some of them can receive interference from other transmitters in other blocks.
- **Cluster**: FAPs grouped in terms of their interference relation. A cluster is the sub-set of FAPs which is processed in a single optimization run, e.g., those within the same building plus some in an adjacent one.
- **Sub-set**: any sub-group within the set of N FAPs.

The best-case for parallelization results when the whole set of FAPs can be split into N independent sub-sets: in this event, the complexity of the optimization depends on the hardware capability to process N independent computations. The complexity grows when an increasing number of FAPs belonging to a certain sub-set interferes with some FAPs of another sub-set and the system has to implement a strategy to deal with the parameters provided by two (or more, depending on the interference scheme among FAPs belonging to different sub-sets) independent optimizations.

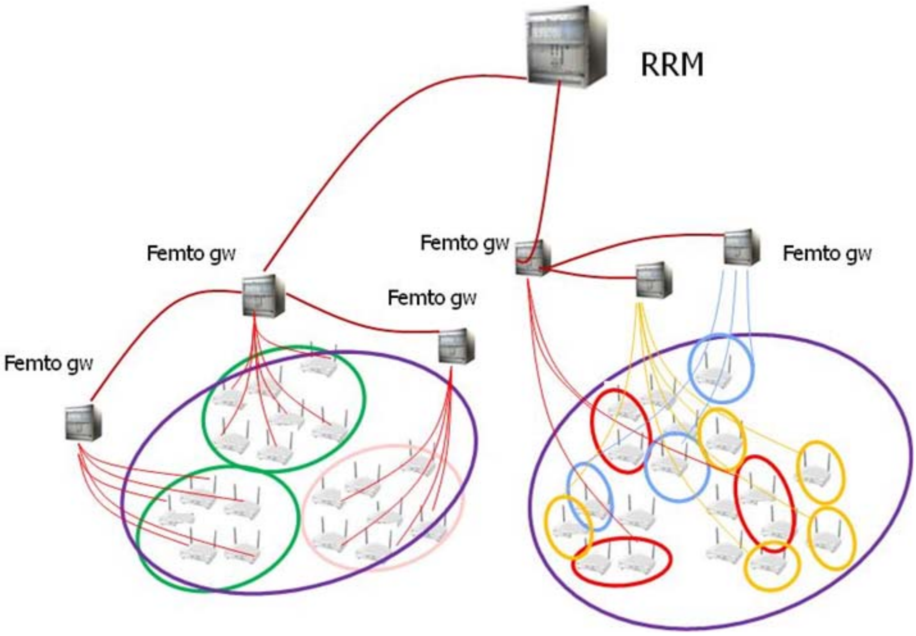


Figure 15. Scheme of clustering with different hierarchy levels. Different colors represent difference clustering criteria adopted (abstract distances) whose knowledge can be available to the network through dedicated tables.

4.2.2 Centralized clustering

The RRM can collect all users' information and transmission parameters, although for a huge deployment of FAPs this would lead to shortcomings related to the amount of data and to requirements on processing. A more realistic approach for the network to have control on possible clusters of users supporting adaptation of heterogeneous users requirements arises from the possibility to deal with aggregated slowly varying metrics got from local subclusters or measured with a timing of order of minutes, or tens of minutes, to have an overall scheme of the traffic levels and services.

4.2.3 Local clustering

Users are aware of others transmitters in range and implement one (or more) of the clustering strategies among mentioned.

4.2.4 Hierarchical clustering: subclusters

Once a cluster is identified, the value of a metric (as mentioned above) considered over the current cluster is available. A cluster can be isolated if only transmitters belonging to it are in range. If some transmitter belonging to that cluster receives the interference of transmitters external to that cluster, one can identify the presence of other clusters. Using the information running through the femto gateways, it is possible to identify and classify clusters of clusters. This way, aggregated information can be fed back to the RRM with limited load on the network in a semi-centralized way.

5 INTERFERENCE MANAGEMENT

In this section the clustering strategies above introduced are discussed at system level in view of interference mitigation from a network point of view. The purpose is to assess the benefits of assuming a clusterization strategy and to compare with optimization criteria described in WP3, based on selfish approaches. Evaluation of pros and contras of methods is based mainly on reliability of a clustering structure (e.g., clusters must have a small overlap) and on the complexity reduction gain obtained by decomposing the problem of (sub)optimal resources assignment with respect to global management. This has as a byproduct the evaluation of how interference, and thus QoS, is affected by implementing or not clustering criteria for an inhomogeneous deployment.

5.1 Sensing capability

The information available to each transmitter about the surrounding environment can be either implemented as an input for distributed optimization procedures, either fed to the core network. In both cases, metrics to evaluate system performances can rely on such information and the system can use them for parameters assignment.

A function of the system simulator has been developed to extract number and identity of transmitters in range of a selected user. Evaluation concerned the set up of a scenario (homogeneous, inhomogeneous or from real map data) and a deployment of users (MUEs, FUEs and FAPs) and analyzing their interference relations in order to select the clustering scheme more appropriate to provide a benefit to the system. Figures presented in this Section refer to the Scenario N1 and N5 developed by SIR, although conclusions apply similarly to other scenarios.

Let us define the significant interferers as the transmitters in range capable to transmit a signal that can be received with a minimum SNR. Such level must be considered as a threshold which must consider specificities of the LTE and typical environment propagation conditions, average interference due to surrounding users in active state and suffers the impact of the MBS DL. Following the simulations designed for activity 5A1 and reported in [Freedom-D51] about the dynamic system simulator, a tradeoff suitable for the analysis performed in this Section has been fixed to a level of 1 dB. This value permits to consider a transmitter in range both an interferer as well as a unit with which is still possible a (reduce) level of communication, such as one that could be included in a cluster, for exmpale to perform a local optimization process.

For an urban environment, Figure 16 displays, at a fixed instant of time, how the number of significant interferers is indeed limited and is given by at most by 12 other users. Simulations have shown how such number can vary of some units but it is anyway limited in the range of less than 20. The effective distribution is reported in Figure 17 and shows how the majority of clusters is composed by 4 to 8 units. Considering that the scenario analyzed corresponds to a real environment map data and the deployment resembles a realistic one without specific limits, this result supports the significance of clustering analysis for network management. Indeed, complexity is reduced both for centralized management (at core level) and for distributed algorithms

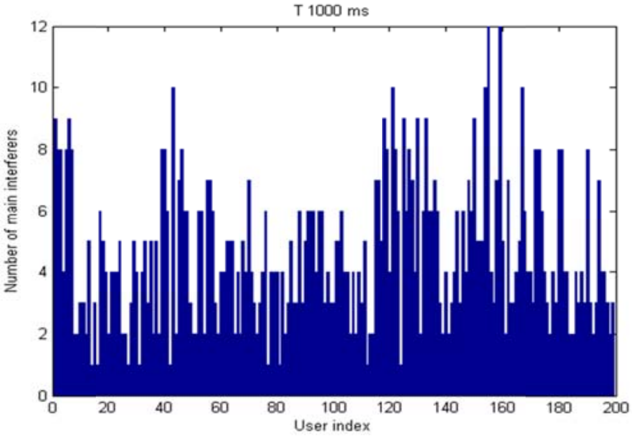


Figure 16. Number of interferers to a single user, shown for a fixed instant of time. SIR scenario N5, with 252 UEs, of which 199 FUEs, 40 MUEs indoor and 13 MUEs outdoor.

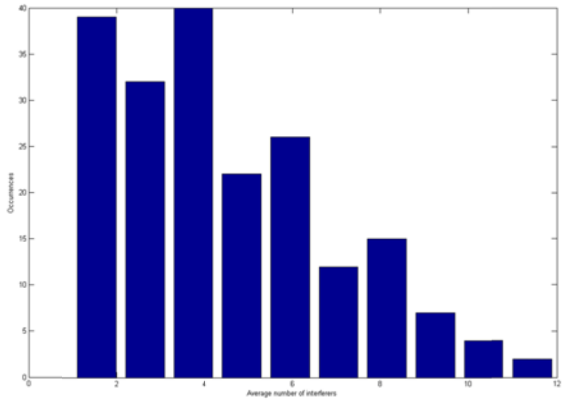


Figure 17. Distribution of number of interferers to a single user. SIR scenario N5, with 252 UEs, of which 199 FUEs, 40 MUEs indoor and 13 MUEs outdoor.

5.2 System evaluation

Inputs and outputs for the resources allocations for all users correspond to series of packets transmitted on the network. The time of packet allocation and repetitions due to errors of ACK/NACK process induce delays on data flow suffered from applications running on mobile terminals and are measured by the PDU-ER for the traffic flow. Thus, a strategy aiming to increase packet flux for groups of users can be reliably related to the link quality between each user and the serving BS (which can be the MBS or a FAP). Performances of groups of users can be implemented by considering aggregate metrics based on average values characterizing the status of the system and slowly varying with time. The system has been tested in terms of different aggregated metrics and of requirements for the backhaul.

5.2.1 **Slowly varying metrics**

The adoption of one or more slowly varying metrics will be considered to compare different approaches in view of a possible reduction of computation for the algorithms. The computing load has to be considered not only in terms of complexity of the single algorithm, but also in terms of time of convergence and necessity to exchange information with other entities of the network.
The necessity of a metric with slow variation with time is related to the convergence time of the algorithms and to the stability of the choice of a set of parameters leading the transmissions for a set of users.

The most fruitful metrics considered so far have proven to be average users SNR, average pathloss and average power increase.

1) Average SNR. It measures the transmission quality for the link serving a user. Depends on power of transmission and activity of surrounding users.
2) Average pathloss. Although is provides a rough measurement of the link quality, it provides an information independent on activity of other users.
3) Average power increase. Given a period of transmission, average power is given by the energy expenditure over the effective transmitting instants of time. Repetitions of packets, for example as a consequence of bad PDU-ER, force the transmitter to spend more energy for the same amount of net data produced by an application.

A service running on a mobile terminal produces a data flow that could saturate the slots assigned to that user and can give rise to two interesting options for the traffic scheduler, both included in the system simulator. In the first case, the application data flow is too high to be served by the current MCS and transmission power, so that the system sets a higher transmission power with increasingly more favorable MCS. The average SNR per user is at the basis of the method for power allocation considered in [Freedom-5D1], Section 6.1.5, the so-called "target power" (see Section 5.1.4.3 of the same document). Indeed, in that case the SNR is the leading criterion to assign power to transmitters and a minimum service must be ensured to users. The second case is given by an application data flow which, due to PDU-ER level, shows an increase of data queue to be processed. Thus, the system can set a stronger MCS with fixed power, gaining a better PDU-ER and then transmitting packets more frequently but with fewer errors, thus offloading the queue and providing a better service to the user. Both cases are well treated by considering the above mentioned metrics.

The following plots refer to the Scenario SIR N1, whose geographic deployment corresponds to Figure 18.

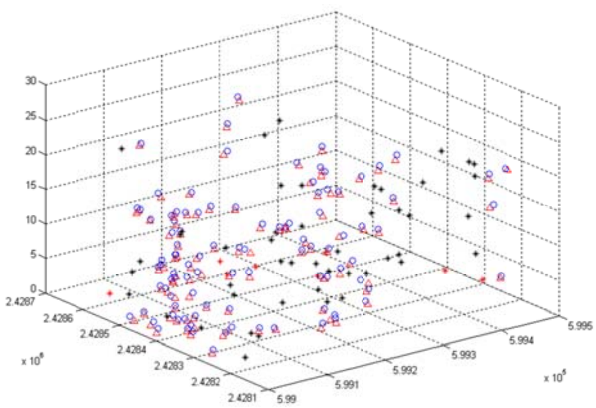


Figure 18. Deployment of SIR scenario N1, with 153 UEs, of which 98 FUEs, 47 MUEs indoor and 8 MUEs outdoor.

Several evaluations of pathloss and simulations performed in [Freedom-D51] suggest that a threshold of 120 dB can be considered as a value to distinguish a major impact of the MBS transmissions over UEs.

Figure 19 reports the average pathloss in dB between each transmitter and the MBS, showing how relatively few users are below such threshold. First 98 IDs are FUEs, then 47 indoor MUEs and 8 MUEs outdoor. Few indoor users and most outdoor ones are under a significant influence of the MBS.

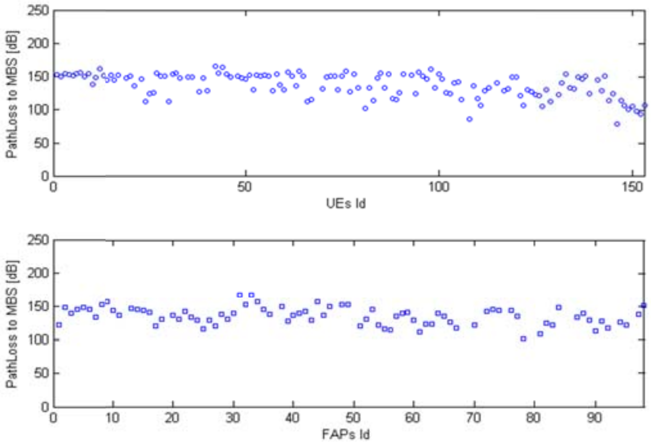


Figure 19. Distribution of pathloss in dB for all transmitters vs MBS. SIR scenario N1.

The analysis of Figure 20 and Figure 21 provides a clear signal of the limited number of transmitters in range, expressed by the pathloss values in dB and considering the sets FAPs/UEs, of FAP/FAP. Inclusion in a cluster at system level and measurement of average SNR can include only users spotted in the figures by colors blue to red.

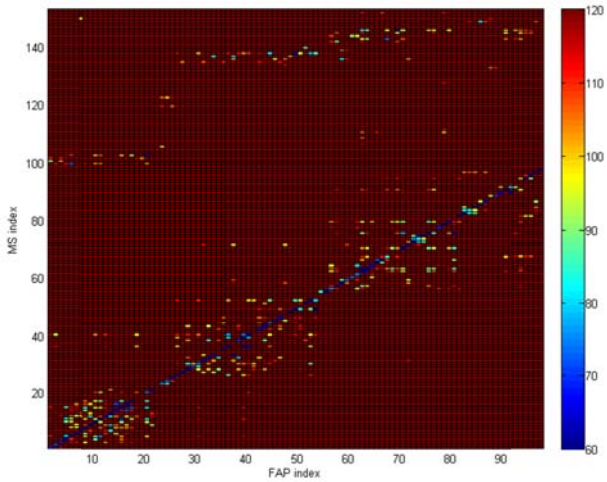


Figure 20. Distribution of pathloss in dB for all combinations FAP/MS. SIR scenario N1.

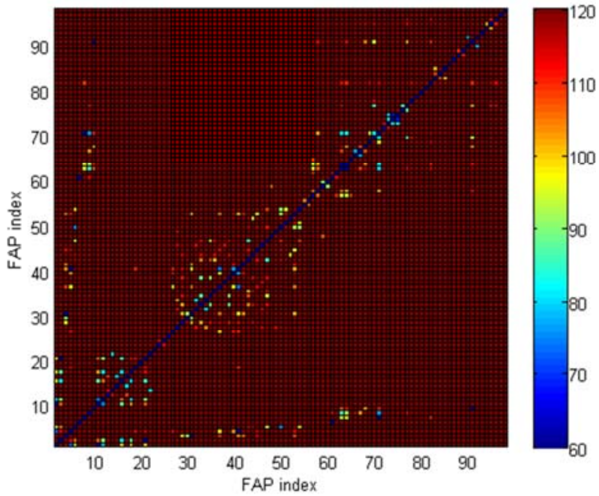


Figure 21. Distribution of pathloss in dB for all combinations FAP/FAP. SIR scenario N1.

5.2.2 Backhaul load

Simulations considered the effective backhaul service provided by the fiber/xDSL link and its limits, together with the load required by the optimization strategies to run, i.e. the exchange of information among users. Different levels of backhaul quality have been included, i.e. excellent (e.g., fiber with minimum guarantee), good or average (e.g., xDSL). Parameters include evaluation of backhaul delay and jitter, as input from WP6, and are useful as input to business model treated in 2A3. A detailed analysis of the impact of backhaul quality has been performed in 5A1 and reported in [Freedom-D51].

5.3 Scalability

5.3.1 Cluster level

In both centralized and local clustering, the network can implement optimization strategies or evaluation (slowly-varying) metrics describing system performances for a limited set of users. The optimization algorithms, especially those proposed for a centralized approach and requiring a significant computational load, can have faster convergence in scenarios with a limited set of users. Let us describe how an optimization strategy is applied to a system split in clusters with units logically belonging to more than one cluster.

Labeling the generic cluster as p_j, the optimization algorithm (for example, the GO) is run on each cluster Λ_{pj} providing a set of output parameters (for example, transmission power and band allocation) for every user in the cluster. On the other side, such output provides two parameter values for all r_j FAPs lying within the intersection. If the algorithm has to be iterated, the system can set an initial value of parameters before proceeding by two modalities: swap or average of the obtained values (see eqs. (1)-(2)) before running the algorithm several (typically a dozen) times over each cluster. Initial values for the next run is chosen as

- for FAPs parameters with unique value, take last parameter value;
- for those r_j FAPs parameters double valued, swap or average values.

Finally, two stop criteria are implemented: one is achieved when the difference between parameters values obtained at two successive iterations fall below a given threshold (e.g., 10^{-1}); the other is simply related to the assignment of the maximum number of iterations. In case convergence is not under threshold when the stop is reached, a unique value is obtained by averaging such two values and fed to the FAPs to be used for transmission.

Considering the GA case, the constrained search for (sub)-optimal parameters starts from random (satisfying the system constraints) initial values and outputs the (sub)-optimum value for the transmission power to adopt for transmission between each FUE and the corresponding FAP. Given the power levels p_{scl1} and p_{scl2} coming out from two GAs running on the sub-cluster *scl*1 and *scl*2, before next iteration the system can implement the two mentioned options to select which value will serve as initial condition for the next run. The *average* or the *switch* are expressed as

$$p^{out}_{scl1} = \frac{p_{scl1} + p_{scl2}}{2}, \quad p^{out}_{scl2} = \frac{p_{scl1} + p_{scl2}}{2}, \tag{1}$$

$$p^{out}_{scl1} = p_{scl2}, \quad p^{out}_{scl2} = p_{scl1}, \tag{2}$$

respectively. At next step of optimization, p^{out}_{scl1} and p^{out}_{scl2} will be adopted as initial values, and so on, until the constraint is fulfilled. The choices both for setting the output power value and for the constraint type (threshold value or maximum number of iterations), provide similar results and do not affect the computing time. Simulations show that both criteria bring to convergence of the optimization algorithm.

5.3.2 **Clusters of clusters**

5.3.2.1 ***Parallelization topologies***

The analysis of the cluster structures leads to identify several topologies of interest to investigate the scalability of the system optimization methods.

We will describe a *ring topology* and a *blocks topology*. The first is an abstraction to tackle a system of FAPs which interfere with the closest ones only, whose number can be indeed high (several tens) and the optimization is split among $N_{FAPs}/2$ very fast sub-processes. The second topology proposed represents several sets of FAPs. The interference to be considered can occur within FUEs belonging to the same set, and for some of them at the borders it can occur also with transmitters in an adjacent set.

5.3.2.2 ***Ring Topologies***

Dealing with interference among nearby FAPs can be successfully approached on the basis of the topology underlying the propagation distances characterizing the environment. This case has been tested for the GA optimization in a scenario in which the frequency bands have already been assigned by other resources, such for example by a former GA-based algorithm parameters search, thus corresponding to the case of different transmitters competing within one frequency chunk.

The idea is to propose a method to identify some sub-clusters (typically including 3 FAPs each) over which running fast GA algorithms. A precise strategy has been implemented to deal with FAPs belonging to two adjacent mini-clusters and is detailed by Eq. (1) or Eq. (2).

5.3.2.2.1 Ring-next, Ring-twist and Ring-generic

The whole set of FAPs can be considered as belonging to a cluster schematized as a ring where every FAP interferes only with few nearby ones. There are several levels of complexity in the interaction between FAPs increasing from a pathloss matrix with the diagonal form as for example the one shown in Figure 23, to less regular ones.

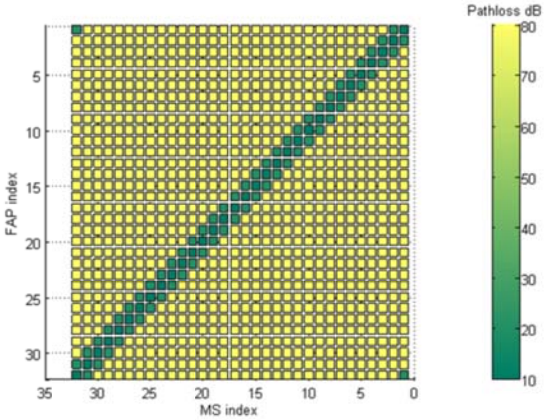


Figure 22. Pathloss representation for a system of 32 FUEs with a ring-next topology.

Two examples in Figure 23, show on the left the topology that we call *ring-next* and on the right the *ring-skip*. The arrows represent the link between those FAPs/FUEs which interfere each other; in this case, every FUE parameter search needs to include three units at a time (a sub-cluster) in order to cover the whole set.

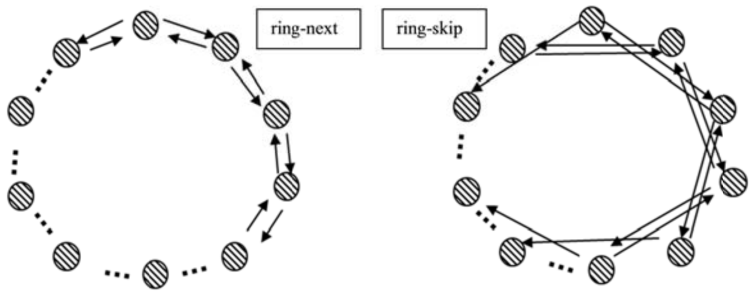


Figure 23. Example of ring topologies. Left: ring-next. Right: ring-skip.

If the topology of interference gets more complex, as for example the one represented in Figure 24, the deployment reduces to the type of a generic one (addressed in previous Sections) without topology features useful for analyzing the scalability.

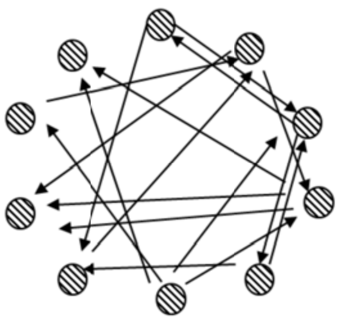


Figure 24. Ring topology without hints for addressing parallelization and scalability.

To study the parallelization and scalability for a system of FAPs in Figure 23, we follow the steps:

1. Identify $N_{FAPs}/2$ sub-clusters provided by groups of three, having at most one unity in common.
2. Run the GA on every sub-cluster.
3. Set the double-valued quantities (see Figure 25, right panel).
4. Repeat steps 2 and 3 using the GA output as initial condition for a new run, until a stop criterion is fulfilled (it can be a threshold on the difference among two double-valued parameters, or a maximum number of iterations).

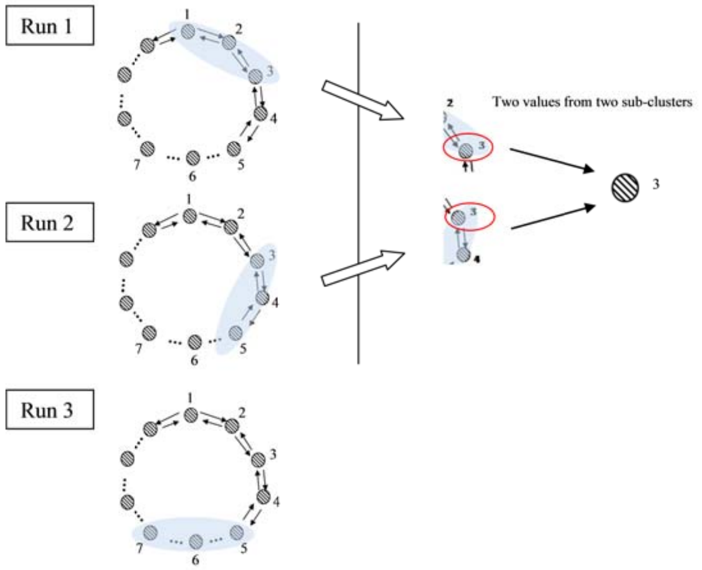


Figure 25. Scalability of the ring topology iterating the GA over the sub-clusters.

Let us consider for example the process in Figure 25 and focus on FUE number 3. It belongs either to the sub-cluster highlighted at step 1, or to that highlighted at step 2. At the next step of the GA involving the users highlighted at runs 1 and 2, p^{out}_{scl1} and p^{out}_{scl2} will be adopted as initial values, and so on, until the constraint mentioned in step 4 is fulfilled.

5.4 Optimizations strategies

5.4.1 Centralized resources allocation

5.4.1.1 *GA Optimization over the ring*

A system with topology of type *ring-next* has a pathloss matrix represented as in Figure 26, which is characterized by a minimum for the elements on the diagonal, a slightly higher value on the two secondary diagonals and the highest values for all other elements. Clusters are composed of 3 adjacent users with one unit at the intersection among two nearby clusters. The algorithm is fast, in the sense that the small number of variables to be optimized allows a small population size (less than 10) and few generations (less than 15) to converge. In terms of time this corresponds to less than 200 frames.

For details about GO terms we refer to [Freedom-D32].

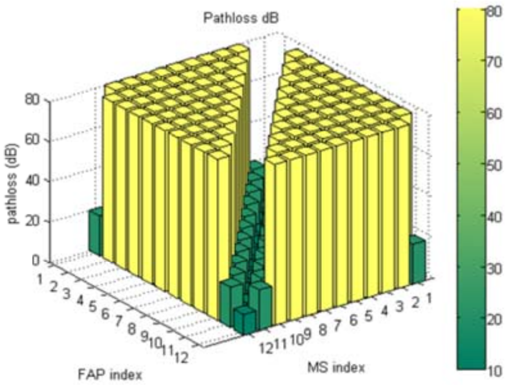


Figure 26. Pathloss representation for a system of 12 FUEs with a ring-next topology.

5.4.1.2 *Blocks Topology*

The FAPs deployment in a specific environment (e.g. urban, suburban) determines a characteristic structure of the signal propagation due to some physical peculiarities of the environment itself. A building with several floors, each accommodating a similar (often the same) number of apartments with similar structure of internal walls will give rise to a pathloss matrix with a typical structure: a number of blocks along the diagonal equal to the number of floors. The resources of the system can be aggregated by several means:

- The FAP can sense its environment;
- The interference can be evaluated by a centralized unit at RRM level;
- The RRM can make a guess at system level and adapt it to the measurements fed back by the single FAPs.

The pathloss can thus be estimated by a measurement or guessed by simulation and its structure determined by setting thresholds to let emerge it. If the RRM has information about where the FAPs are installed (this is indeed always the case) the system can implement a clusterization scheme in order to speed up the parameters optimization algorithm and to divide the whole system into smaller sub-systems.

The assignment of a FUE to one cluster or to another comes from empirical considerations based on the above mentioned criteria and is expressed by the pathloss structure. In this activity DUN is considering the presence of a cluster structure and how to deal in the case of a not isolated cluster but with other nearby ones geographically distributed (see Figure 27).

In the case of several clusters, as in a urban scenario with several building over a grid and separated by road, it is straightforward to indentify to first approximation a cluster of FAPS as FAPs deployed in one building. In presence of several clusters, some FUEs belonging to a cluster interfere with some others in the nearby cluster; the same is true for the next cluster and so on.

The interference among nearby clusters is more relevant for the FUEs near the borders and will be negligible for the others.

The algorithm dealing with this problem is the following:

1. identify different blocks;
2. identify FUEs at the intersection interfering with users from two blocks;
3. define a cluster as one block plus the maximum number of FUEs interfering simultaneously with them from a nearby block;
4. run the GA parameters search separately on each cluster;

5. set the power values for the FUEs at the intersection of two clusters;
6. repeat steps 3 and 4 with 5 until a stop criterion is fulfilled.

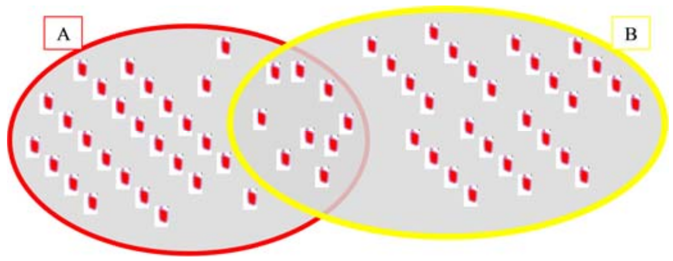


Figure 27. Example of nearby blocks of FUEs.

Similarly to the case of the ring topology, where the problem was the scaling from the sub-cluster level of three MSs to the entire set constituting the ring, in the blocks scheme here introduced the overall set of MSs is divided in blocks (labeled as A, B, C, see Figure 12). The GA optimization is run over the reduced set of MSs belonging to each cluster, composed of MSs belonging to different blocks, i.e. allowing to parallelize the computation. Analogously, the power levels assigned to the MSs lying at the intersection of different blocks follow from Eq. (1) or Eq. (2). We remind that blocks refer to the geographical deployment, clusters refers to the GA optimization.

The adopted scheme, on the basis of the PHY layer parameters implemented so far, addresses a scenario with three blocks emulating a deployment such as in Figure 12 with an overall pathloss matrix represented as in Figure 28, whose parameters are the number of FUEs per block N^{MS}_{block} (the same for all blocks) and the number of FUEs simultaneously interfering with two blocks $N^{MS}_{overlap}$.

The use of the term "block" is to keep reference to the geographical deployment of FAPs such as the set of devices that can be inside a building and whose position can be mapped to belong to an aggregate easily recognizable. The term "cluster" refers to the set of FAPs mutually interfering at PHY level. Thus, the GA processes one cluster at a time (i.e., in parallel) whose FUEs can belong to different blocks. In the diagram of Figure 12**,** for example, one can devise the cluster population as:

1. Cluster 1 includes all FUEs from block 1 and some from block 2;
2. Cluster 2 includes all FUEs from block 2, some from block 1 and either some from block 3;
3. Cluster 3 includes all FUEs from block 3 and some from block 2.

The first example tested is the one in Figure 28, for which $N^{MS}_{block} = 5$ and $N^{MS}_{overlap} = 2$ and the colors highlight the FUEs interfering with next block.

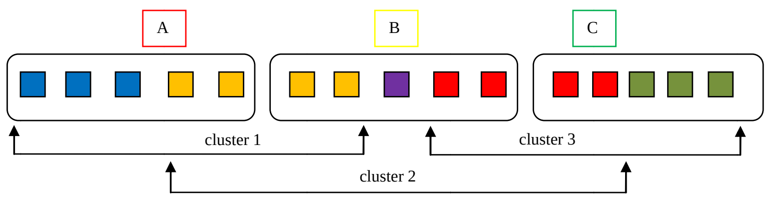


Figure 28. MSs interference scheme for 12 FAPs deployed in three adjacent blocks. FUEs of the same color underline the necessity of a cluster including the current block and some FUEs from nearby blocks.

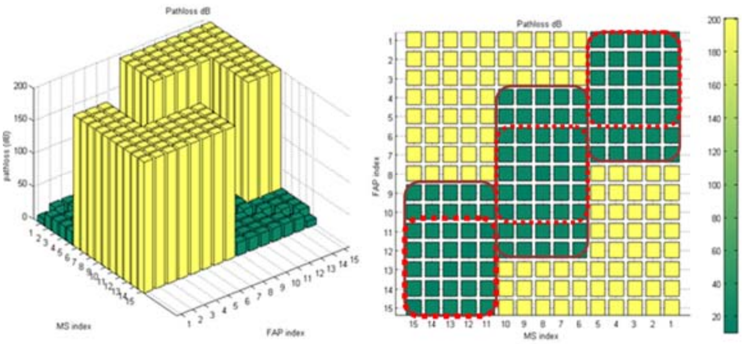


Figure 29. Graphic representation of the pathloss matrix for a system of 15 FUEs, with an overlap of 2. The vertical shapes on the right panel highlight the three sets of FUEs which are processed at every step of the GA while the dotted shapes refer to the different blocks.

5.4.2 Scheduling in distributed RA algorithms on the LTE frame structure

In the LTE specifications, users can allocate power and bits (i.e choose a constellation) to blocks of a given number of subcarriers (12 in most of the cases) and for a predetermined amount of time. These are referred as physical resource blocks (PRBs). Allocation of PRBs is handled by a scheduler. The radio frame structure has time duration of 10 ms consisting of 20 time slots. Each slot has a duration of 0.5 ms and is divided into 6 or 7 OFDM symbols intervals (depending on the chosen format), which may also have even durations. The size of a PRB in the time dimension is one time slot.

In this section we will show how the dynamic resource allocation algorithm proposed in section 7.3.2 of [Freedom-D3.2] under a Markovian statistical model of the macro-users activity can be scheduled on the LTE frame structure.

More specifically, we evaluate the rate loss for the max-rate game due to its running time: the time available for data transmission becomes shorter when a fraction of time slots is spent for letting the algorithm run and converge. The impact of this signalling overhead depends on two parameters: how many iterations of the algorithm are desired in each run, and how often the algorithm is run, this last parameter being inversely proportional to the time horizon over which the algorithms is set to allocate resources.

In our simulation results we have considered the macro-users activity on 200 frames corresponding to 4000 time slots. The number of time slots n_c needed for the convergence of the sum rate game proposed in section 7.3.2 of [Freedom-D3.2] (under a first-order Markovian model assumption for the macro-users activity) is given by[1]

$$n_c = \left\lfloor (2 \times N_{Faps} + 1) \times N_{it} / 7 \right\rfloor \text{ [time slots]}$$

Where N_{Faps} represents the number of active FAPs and $N_{it} = 4$ is the number of iterations needed for the algorithm to converge. More specifically the algorithm can be scheduled as follows:

1. For a time equal to 1 OFDM symbol interval each FAP can estimate the macro-user interference power assuming that all the MUEs and FAPs are not transmitting;
2. The term $2 \times N_{Faps}$ takes into account the number of slots required for estimating the FAP's interference powers. In details, for a time of duration equal to N_{Faps} OFDM symbol intervals, the FAPs are scheduled to transmit one by one, instead of transmitting simultaneously, so that each FUE can estimate the overall FAPs interference. Finally each FUE one by one transmits

[1] For simplicity, we assume the subframe configuration in which each slot is divided in 7 OFDM symbol intervals of equal duration.

the estimate interference to the associated FAP so that $2 \times N_{Faps}$ OFDM symbol intervals are spent for each iteration of the algorithm.

We are now in the position to evaluate the loss on the data transmission rate due to the time spent for the algorithm to converge. To this end, we assume that all the slots in the 200 frames can be potentially used for data transmission. Under this assumption the rate loss depends on how often the resource allocation algorithm is run. More specifically if we assume that the maximum-rate game is run n_T times on 200 frames the overall time slots available for data transmission are given by $4000 - n_T\, n_c$ where n_T can be also expressed as $n_T = \lfloor 4000/(n_d + n_c) \rfloor$ denoting with n_d the number of time slots over which the FAPs allocate every time that the algorithm is run.

Therefore, the algorithm works as follows:

1. Each FAP observes for a single time slot the macro-user activity;
2. n_c time slots are spent for running the maximum rate game, assuming that for this time interval the macro-user activity does not change. The game predicts the time-frequency power allocation over the next n_d time slots.
3. After n_d time slots return to step 1.

As a consequence, there exists a trade-off between the overall rate and n_T: for a fixed n_c by increasing n_T the available data transmission time slots n_d decrease. In order to quantify this behaviour we introduce the parameter $\eta = \dfrac{n_c}{n_c + n_d}$, representing the loss in terms of data time slots due to the running time ($n_c/2$ ms) of the game. Observe that $\eta \to 0$ when $n_d \gg n_c$, i.e. if the convergence time can be neglected with respect to the data transmission time, while $\eta \to 1$ if the loss in the transmission time due to the convergence time is non-negligible.

Therefore we report in Figure 30 the sum of the rate per-FAP over 200 frames and 25 frequency resource blocks versus the parameter η. We can observe that as the rate loss is low, i.e. for small η values the achievable rate is higher and it decreases as we increase the frequency with which the resource allocation game is run over 200 frames. Furthermore it can be noted that as the number of active FAPs is increased (lower subplot) a lower rate can be achieved due to the higher interference levels among the FAPs.

Finally, from Figure 31 we can assess a fundamental feature of the proposed algorithms. As extensively discussed in section 7 of [Freedom-D3.2] the predictive behaviour of the resource allocation strategy assuming that the macro-users activity can be modelled by a first order Markov chain is more effective when the number of time slots n_d composing the block over which the algorithm is performed is low. As we increase n_d the mismatching between what is predicted and the real interference increases.

According to these observations, in Figure 31 we report versus n_d the relative gap $\dfrac{R_{nck} - R_{sk}}{R_{nck}}$ between the rate with non-causal knowledge of the interference activity, denotes as R_{nck}, and the rate obtained with statistical knowledge of the macro-user activity R_{sk}. We can note that, as expected, such performance measure is an increasing function of n_d. What is interesting to notice from Figure 31 is that the knowledge of interference statistical parameters, if properly exploited as in the method proposed above, yields a rate very similar to the ideal case assuming non-causal knowledge (the percentage loss is less than 0.004).

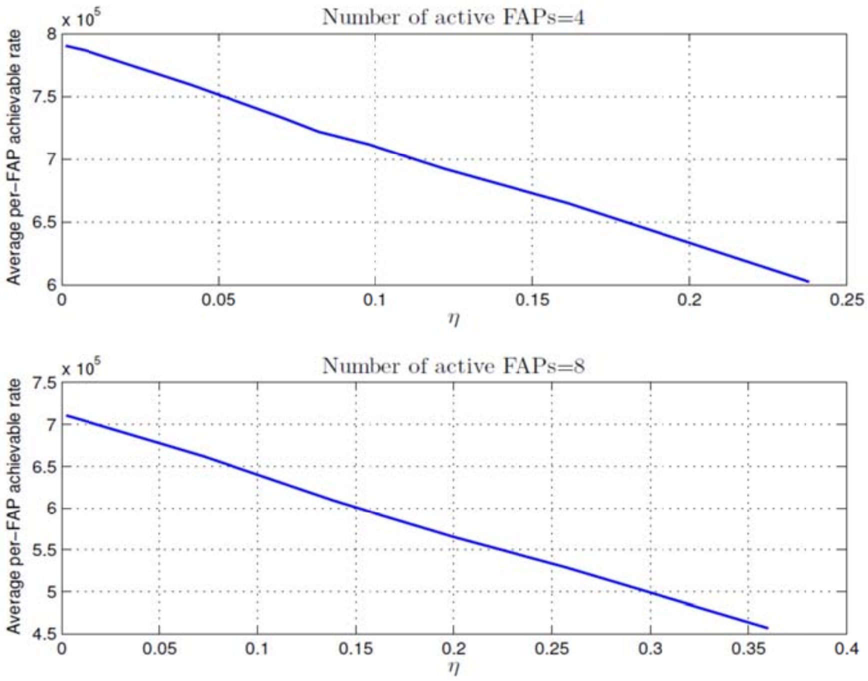


Figure 30: Average per-FAP achievable rate versus the parameter η.

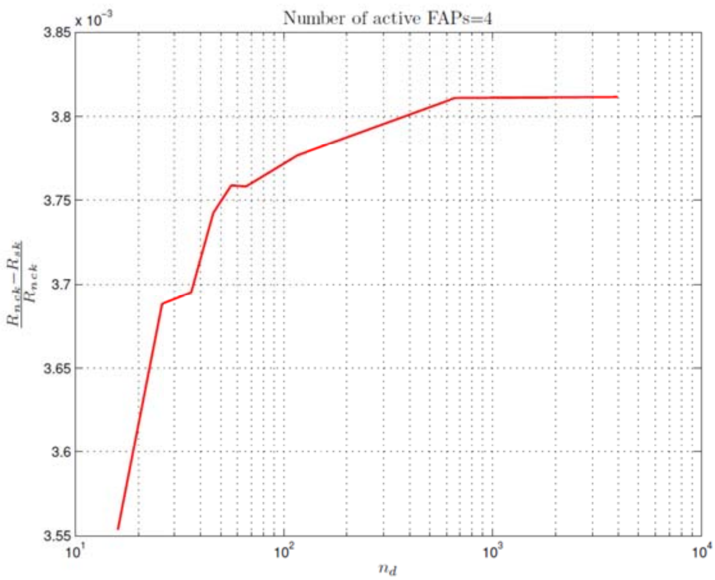


Figure 31: Relative gap between the rate with non-causal knowledge and the rate with statistical knowledge of the macro-users activity versus n_d.

6 METHODOLOGY FOR SYSTEM LEVEL SIMULATION

In this section the methodologies introduced in the previous part will be considered in view of a comparison of the network properties (SNRs of users, traffic load, fairness, etc.). The dynamic simulator has been designed to evaluate system performances to address problems for both activities 5A1 (reported in [Freedom-D51]) and 5A2.

The objective of this part of activity is to complete and merge the evaluations at system level regarding the impact of a femto network in a cell with focus on traffic and applications running on mobile terminals. Several system level evaluations are a follow up of 5A1: the output measurements and QoS indicator for the activities in 5A1 could be summarized by SINR levels over time and their impact on transmission events, while the "event-unit" is the transmission by a MS of FAP. On the other hand, in the present activity the SINR (and its time variation) can be considered as the input parameter at the basis of the system processing whose basic "event" is the single packet exchanged by a certain application running on the mobile terminal.

6.1 System simulator

The dynamic simulator manages the evolving aspects of the network. The dynamics is given mainly by two factors:

- different applications running on a smartphone generate a variation over time of packet flux to/from that unit. Such data flow is encoded and transmitted following a scheduling function which manages queues and simulates retransmission of NACK packets, thus request of resources varies from subframe to subframe;
- the environment changes over time due to motion of transmitters or motion of object around transmitters (e.g., a car passing by, a door opens or closes) on the timescale of human movements, providing significant changes in the pathloss (and consequently on the SINR) on the timescale of few frames (i.e., some tens of ms).

The system simulator addresses both cases, focusing attention depending on the problem under analysis. The output is expressed, for example, in terms of advantage or disadvantage of the MBS offload measured in terms of resources otherwise made available or energy consumption. Different evaluations about possible choices are left as business case issues under the MNO decision
At this level, system simulator is developed in parallel for 5A1 and 5A2. We refer to [Freedom-D51] for the dynamic simulator structure.

6.2 Simulator principles

Simulator developed for this activity is based on the dynamic simulator elaborated in WP5 (see also [Freedom-D51]), which is an event-driven system level simulator. Overall simulator scheme is represented in Figure 32. One aspect is given by the evaluation of the clustering strategies and their impact on network performances. The simulator has a modular structure in which every block corresponds to a functional aspect of system: structure, geometry, propagation, interferences, management, applications etc. The system evaluation is based on a set of system-level metrics allowing the assessment of network performances from a system-level perspective.

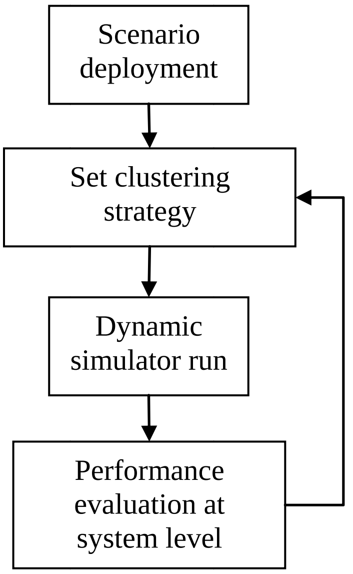


Figure 32. Schematic representation of the dynamic simulator

6.2.1 Transmission event

The system is represented as macro- and femto-network. The macro network (MBS and MUEs) has a synchronized time frame, i.e. when BS is in DL, all MUEs are silent. The femtocells act as independent BSs and thus can realize different synchronization cases, which for the purposes of this document they are not relevant and have been presented in details in Section 6.1.3 of [Freedom-D51] Although considered as a separate entity, the femto network is a unique system simulated as the sum of small subsystems made by the single FAPs. Indeed, each FAP has its own scheduler to manage data traffic between the mobile users registered to it. Every user has different types of traffic over the FAP which, in total, contribute to the backhaul load toward the core network over the IP link.

The system simulator has a module to emulate data packets inclusive of application overhead for each application of each user. Each event of simulation is given by a packet of data and corresponding overhead requested as a service by the user to its serving BS (MBS or FAP).

The traffic types emulated are described in details in Section 5.6 of Deliverable [Freedom-D21] and have been implemented in the dynamic system simulator in three categories: VoIP, FTP and bursty.

- VoIP. Is modeled as a two state Markov process and adopting the G.711 codec. Average bitrate is 64Kbps. Voice payload size is 160 bytes, 20 PPS. Further protocol header assumptions to compute IP overhead are included: 40 bytes for IP, 8 for UDP, 12 for RTP, 18 bytes for Ethernet headers, FCS and CRC.

- FTP. Uniform flux of data packet with small variations in packet dimensions and inter-packet delay of about 10%. Such values vary depending on average data throughput. Simulator allows to set output average FTP throughput and packet dimensions.

- Bursty. Packets dimensions and inter-packet delay have higher variability of order 80%. This type of traffic is designed to emulate HTTP, gaming or application driven data requests.

Simulations have been run for three types of users:

- Type 1. User has voice traffic only, encoded as VoIP.
- Type 2. User generates VoIP and FTP traffic.

- Type 3. Users generate three types of traffic: VoIP, FTP and bursty.

In view of the comparison of system evaluation of traffic flow for users attached to a FAP or to the MBS, a script emulating the traffic reproduces exactly the same packet flow for the two cases: the data flow is available separated for each application for the user in the femto network; the same data flow is merged as a unique data flow for processing when the same user is a MUE attached to the MBS.
The type of data flow for a user of Type 3, with a richer set of applications running on the mobile, is depicted in Figure 33. Different applications (FTP, VoIP and bursty traffic) generate a packet request of data as represented by filled markers in the figure. Empty red squares are the sum of all data request. Figure 33 shows the net request, i.e. the number of bits, including overheads, which need to be transmitted in order to have a reliable QoS. Then, scheduler packs into PRBs according to MCS and real time slots of transmission follow one of the possible structures for the subframe partition as summarized in Table 2.

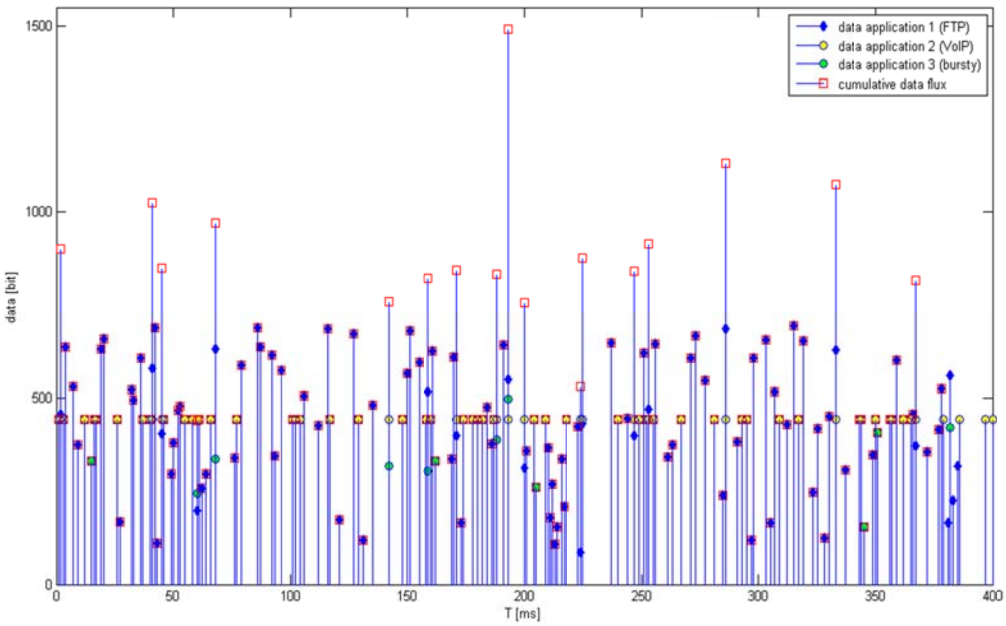


Figure 33. Example of data load for a user with three types of traffic.

	Subframe structure
case 0	[-1 0 1 1 1 -1 0 1 1 1]
case 1	[-1 0 1 1 -1 -1 0 1 1 -1]
case 2	[-1 0 1 -1 -1 -1 0 1 -1 -1]
case 3	[-1 0 1 1 1 -1 -1 -1 -1 -1]
case 4	[-1 0 1 1 -1 -1 -1 -1 -1 -1]
case 5	[-1 0 1 -1 -1 -1 -1 -1 -1 -1]
case 6	[-1 0 1 1 1 -1 0 1 1 -1]

Table 2: Possible subframe partitions slots. 1=UL; -1=DL; 0=includes control packets.

Figure 34 represents the temporal data output for 4 users performing different types of traffic over a longer time scale. For the case of VoIP the maximum packet size and inter-packet time interval are is set according to the G.711 codec, otherwise they are a system parameter and can be changed to mimic other types of traffic, such as FTP at variable rates, HTTP, gaming or video/audio streaming.

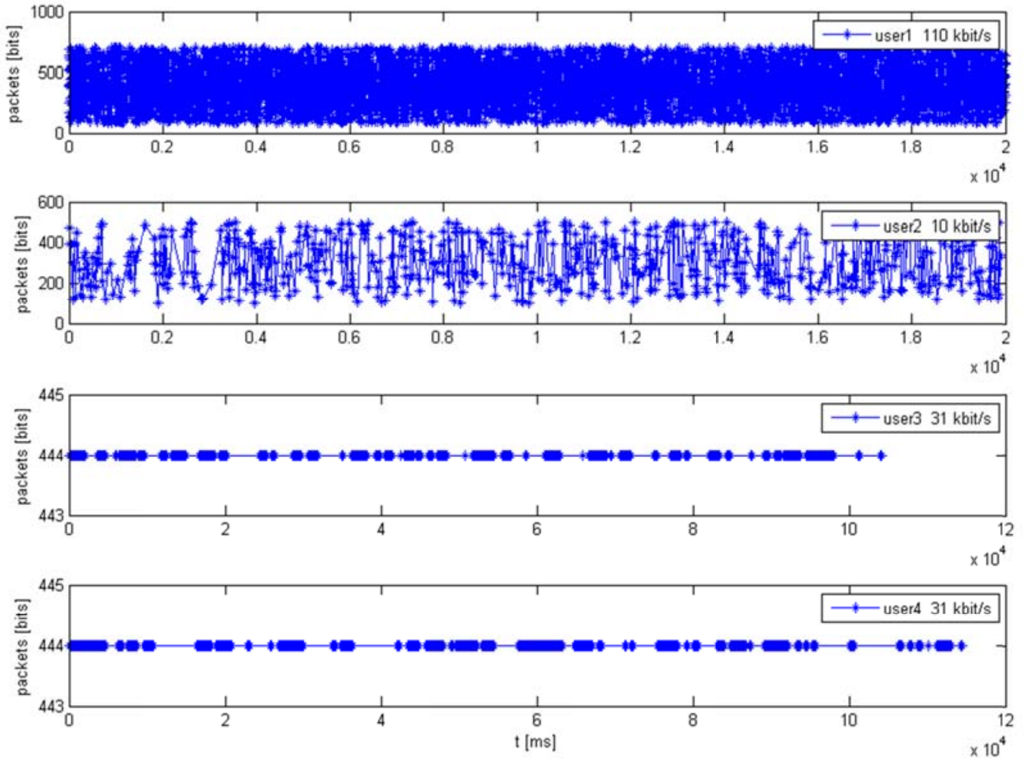


Figure 34. Example of four types of traffic. From top to bottom: FTP high rate, bursty medium rate, 2 users with VoIP codec G.711.

6.2.2 Events sequence

The sequence of events, causing also interference in the network, derives from the overlap of transmission of all users in the network and is represented, as an example, in Figure 35. In this case, the macro network is synchronized with all FAPs of the femto network and the system is supposed synchronized also among FAPs themselves. In this example both MBS and all FAPs adopt also the same subframe structure, so that MUEs and FUEs are simultaneously in DL or UL. The impact at system level of this property has been extensively analyzed in [Freedom-D51].

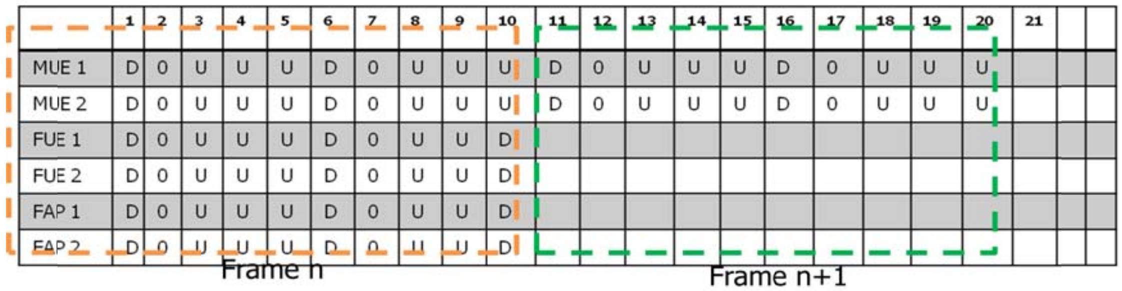


Figure 35. Temporal structure of frames for a set of transmitters. Example of 2 MUEs, 2 FUEs and their corresponding FAPs. MUEs implement transmitting scheme "case 0", FAPs "case 6" from Table 2.

6.3 Key parameters

Coherently with 5D1 ([Freedom-D51]), simulations considered in WP5 regard the following aspects:

- Wireless system (3GPP LTE-A) characteristics;

- Propagation models;
- Interference power models;
- Spectrum usage;
- Traffic models;
- Synchronization error models;
- PHY-layer abstraction and backhaul abstraction (link quality);
- Mobility and handover;

The simulation parameters are directly related to the aspects listed above. The details about these simulation parameters are given in paragraph 5 of [Freedom-D21].

6.4 Performance metrics

A detailed description of selected metrics is given in section 5.2 of [Freedom-D21]. The focus is towards system oriented metrics, describing the efficiency of the overall network. The performance evaluation of a system-level network based on LTE-A standard will allow also to comment on the targets of LTE-A.

6.4.1 **System-level metrics**

Metrics used for performance evaluation at system level (according to the definitions given in paragraph 5.2 of [Freedom-D21]) are:

- Overall cell throughput
- Clusters cell throughput
- Overall spectral efficiency
- Clusters distribution of spectral efficiency
- Overall QoS
- Cluster distribution of QoS
- Fairness
- Call drop rate
- Latency
- Backhaul overhead
- Average power per user.

6.4.2 **User-level metrics**

As a reference, system can evaluate also user level metrics, in order to assess a comparison with a network without implementation of optimization strategies for interference management. For the performance evaluation at user-level the following metrics are selected:

- Distribution of users throughput
- Distribution of users spectral efficiency
- Distribution of users QoS
- Call drop rate per user
- Distribution of latency
- Power per user.

Such metrics can be measured for both MUEs and FUEs. The objective for this type of metrics is to give the performance evaluation of the network as seen by a single user (UE).

7 SYSTEM LEVEL SIMULATOR ARCHITECTURE

7.1 Dynamic simulator

We report here, for simplicity of explanation, the scheme of the system level simulator architecture, in order to underline the interchange of information between DUN and SIR activity, and DUN and INFOCOM activity.
The system-level simulator developed by DUNE has a block-scheme given in Figure 36. Its architecture is based on the implementation of system's functional aspects in a modular structure (architecture based on the modules).

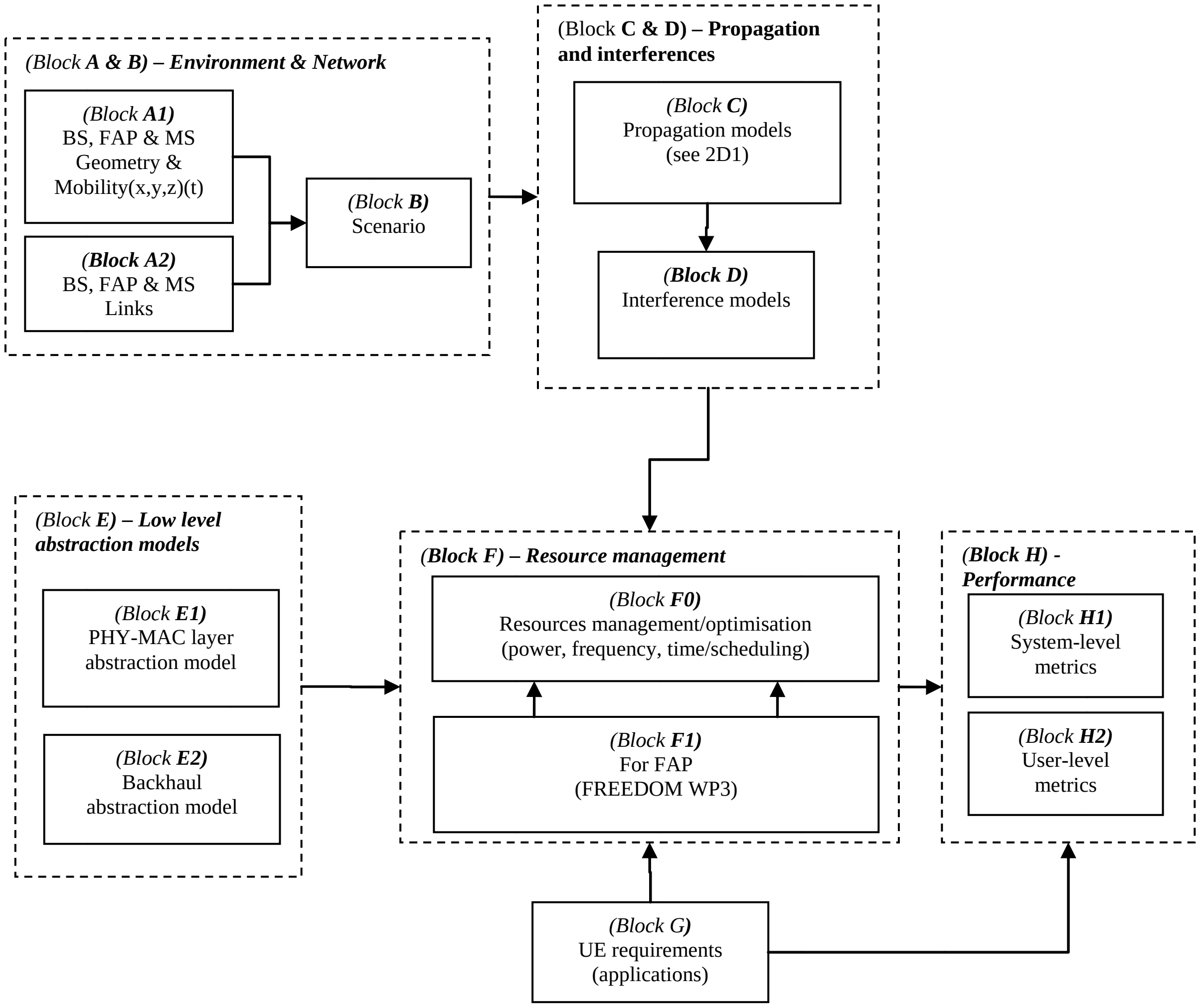


Figure 36. Schematic block diagram of the dynamic system level simulator.

For a dedicated description of the blocks A, B, E, H, we refer to the document [Freedom-D51] while the other blocks are addressed here for their specific reference to the tasks of 5A2.

7.1.1 Environment and network

The network deployment summarizes the three-dimensional coordinates of the position of each MBS, FAP and MS (MUE or FUE) present in the scenario. The mobility of MSs is implemented by considering the variation of their positions as the functions of time and the impact on the pathloss. Then, the definition of the links between BS, FAP and MS (how MS is connected to the network: via which MBS or FAP) is established. Pathloss temporal variation includes both mobility of users and change in the surrounding environment, i.e. human activity or motion of objects (for example, a door opening).

The content of the blocks A and B is covered by WP2 (see [Freedom-D21] for details).

7.1.2 Propagation and interference

The modeling of the path-losses due to propagation between the transmitter and the receiver are composed of: macroscopic path loss, shadow fading and micro scale fading. These path-losses are provided by the propagation module for each UE-BS couple, where the BS is either a MBS or a FAP, but also for each MBS-FAP and FAP-FAP couple when required for simulating coordination.

In a first approach, the pathloss is computed from the analytical models given in [Freedom-D21] and completed in [Freedom-D31], based on a theoretical (or abstract) building representation. The shadow fading is modeled by a lognormal variable with spatial correlation. And the small-scale fading result from the vector sum of the complex channel coefficients generated by the stochastic WINNER II model.

In a second approach, the pathloss and shadow fading are simulated by a site-specific propagation model based on a 3D vector representation of a real environment [Freedom-D31]. As ray-tracing is used, the channel multi-paths are constructed and summed to provide the small-scale fading component. The path-loss is provided either for each resource block or as an average value over the whole signal bandwidth (i.e. small-scale fading component is averaged).
System-level simulations require time-variant channel inputs, i.e. a path-loss that varies during the whole simulation time.

As this simulation time is of order of 1 or 2 seconds, complex UE mobility models have not been considered necessary. The UE motion is represented by a mean velocity and direction. Most channel properties are assumed to be constant. Only the relative phase shift between the channel coefficients is changing, as a consequence of changes in the length of multi-paths. These phase shifts are calculated at different successive UE locations as a function of the multi-path arrival angles and geometry of the small UE move. Figure 37 shows an example time-variant channel realization obtained on a FAP-UE link during 1s.

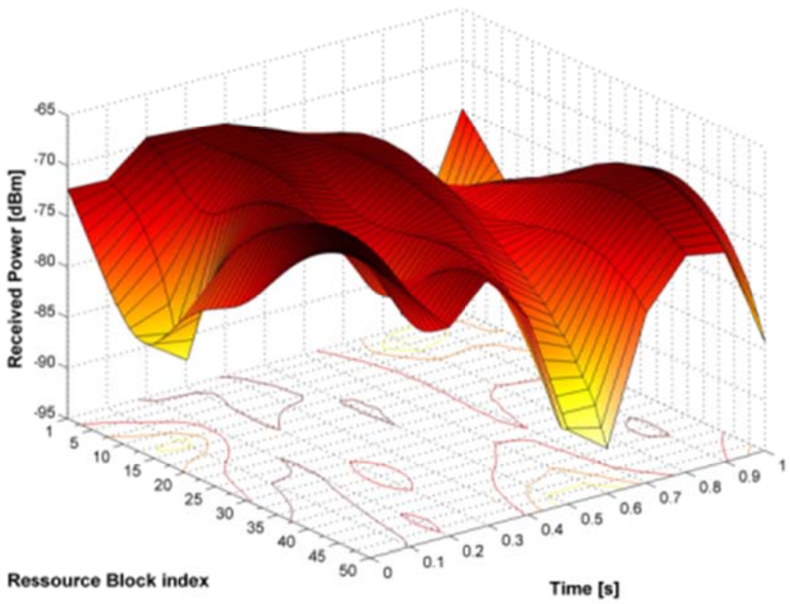


Figure 37: Time-variant channel on a FAP – UE radio link.

Time-variant channel properties are predicted in a different way when the UE is indoors and fixed during the simulation time. The move of human bodies in the UE or FAP vicinity creates channel variations that occur mainly in a bursty manner. The stochastic model presented in [Freedom-D31] is used.

Techniques that exploit MIMO capabilities may require enriched channel realizations. For this reason, the channel module gives the possibility to output additional properties, i.e. all space-time channel properties like delays, departure and arrival angles of main contributions.

Figure 38 gives a schematic view of the propagation module architecture and its interaction with the rest of the simulator. The propagation module is basically composed of the VolcanoLAB platform where all path-loss and channel models described in [Freedom-D21] have been implemented. A VolcanoLAB script generator is run from Matlab® to transform the scenario description (building representation, MBS network, FAP deployment, UE deployment, UE mobility, and possibly indoor human activity) into a command file fed to VolcanoLAB. The channel output matrices are returned in MAT format, which is converted to the format of propagation traces read by the system-level simulator.

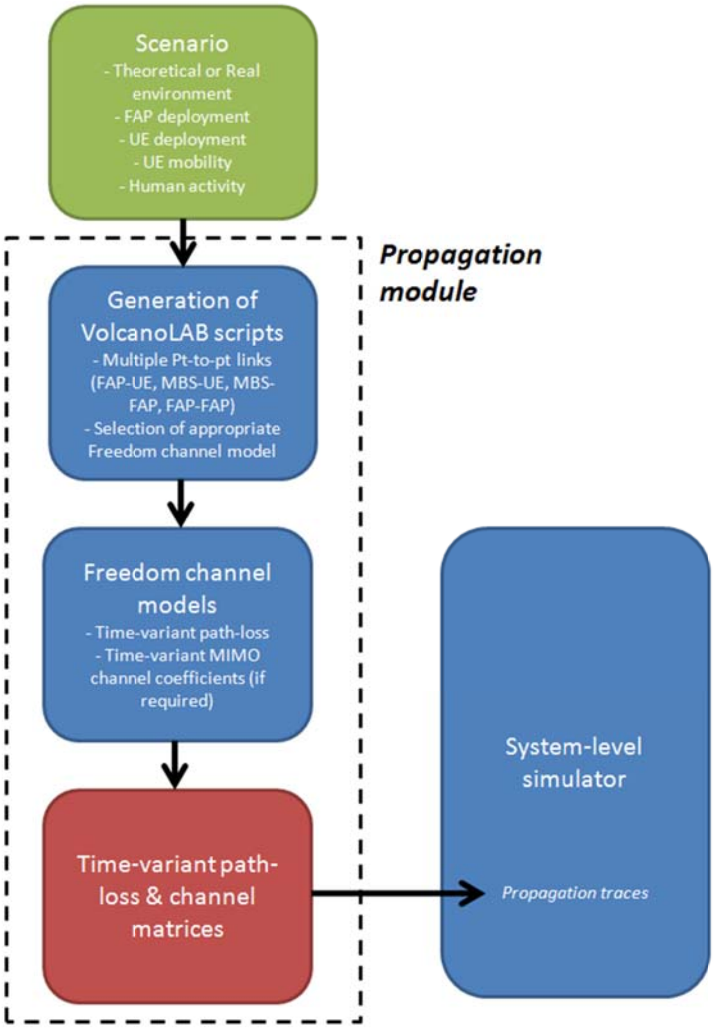


Figure 38: Propagation module: generation of path-loss and channel matrices.

7.1.3 **Low level abstraction models**

The PHY-MAC layer abstraction model and the backhaul abstraction model are represented by block E. The system simulator is based on PDU-ER vs SNR curves for different MCS, allowing the assignment to each transmitter of the appropriate modulation for the propagation conditions.
The MCS is assigned or changed to each user after measurement of the current PDU-ER which varies with interference levels around each transmitter. To avoid excessive changes of MCS, such measurement is performed over a number of transmission opportunities which for the simulator has been fixed to 50 as a compromise for data fluxes with scarce transmission requests and necessity to ensure reliable QoS.

7.1.4 **Resource management**

The radio resource management (RRM) includes the core of the packet scheduler (PS) allocation. It has been implemented both for the MBS where several MUEs compete for radio resources, and for the FAPs where much less users (1 to 4) have to share the corresponding radio resources.

The user scheduler is a function, implemented at BS level (MBS or FAP) which manages the data packets allocations within one single time slot, i.e. one column of the sequence reported in Figure 35.
The scheduler has been implemented taking into account

- Frequency selective channels. The band is divided in PRBs and the central unit knows which are the most favorable channels for each users' transmission.
- Traffic level. A priority engine takes into account the number of packets queued for each user and the priority of the traffic type. A score is assigned following such criteria and a classification is fed to the scheduler. Priority is given to users with longer queues, and VoIP, delay sensitive applications.
- Optimization strategies. If an optimization strategy has been implemented (for the femto network) simulator takes into account possible clustering strategies and slowly-varying metrics describing parts of the network.

In particular, the core unit is functional for transmitting aggregate slowly-varying metrics across the network to implement hierarchical clustering, including the scheduler engine for the single FAPs which is also affected by the presence of clustering. On the basis of information about the links (if requested by the optimization algorithms implemented) and the UEs requirements (services requested by UEs), the RRM assigns the radio resources in terms of system efficiency criteria (time-frequency elements) and power to every single transmission. In case of distributed algorithms, the action of RRM can be reduced to scheduling traffic on the basis of competitive resources assignment run in a decentralized way.

Figure 39 represents one of the two temporal slots which constitute the basic unit of the LTE PRBs resources scheme. The scheduler has to fill the PRB texture by assigning the most favorable frequency interval to all users.

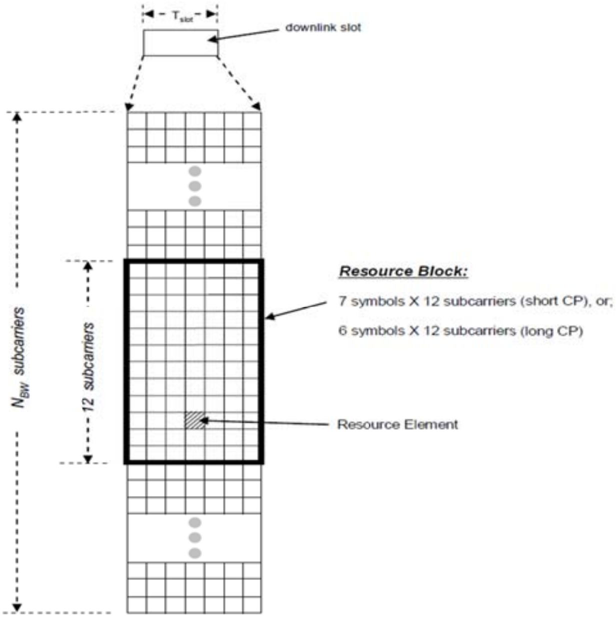


Figure 39: Design of Physical Resource Block (PRBs).

Figure 40 represents an example of packets flow in the network in the case of 4 users, 2 of them with FTP traffic and 2 with VoIP (codec G.711). The red and blue symbols represent the net data packets to be sent in the network and the effective data sent (including packet re-sending repetitions due to packet error rate). The peaks present around T=500ms are due to the worsening of SINR (for that user in this specific example) are the packets that must be resent and accumulate in queues until a stronger MCS is assigned to that user.

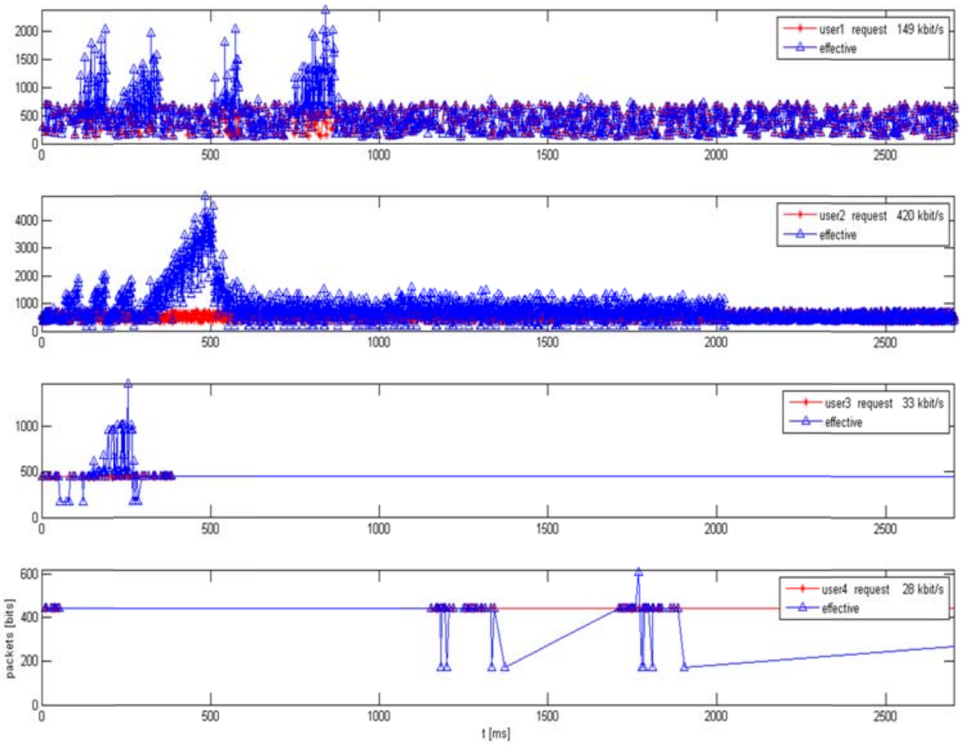


Figure 40: Effective data packet allocation by a round-robin scheduler for different types of traffic requests: red symbols, packet requests without errors; blue symbols effective packets transmitted, including retransmisssions. From top to bottom, 2 users with traffic FPT-like and 2 users with VoIP (codec G.711).

7.1.4.1 *Adaptive MCS*

The architecture allocation of data packets is summarized in the block scheme of Figure 41: the traffic requests are synthesized at the millisecond scale coherently with the LTE standard. Packets are transmitted in the order set by the scheduler and correctness receipt is evaluated. Packets received with errors are postponed and added to the transmitter's queue.

At the beginning of the simulation, a MCS is assigned on the basis of the initial SINR. As the flux of packets proceeds with time, PDU-ER changes when SINR varies due to the environment evolution and activity (e.g., dynamics of the surrounding transmitters) and each unit measures the current PDU-ER by evaluating the number of packets with negative ACK from the companion receiver (PDU-ER is indeed evaluated at level of the radio link, and not at application level). The current PDU-ER is computed averaging the last 50 transmission events, whose effective time lapse depends on the application type. Such value is chosen in order to prevent excessive changes of MCS, although maintaining a sufficient QoS.

The MCS module takes into account both improved or worsened link conditions by setting an upper and a lower threshold. At each simulation time epoch, PDU-ER is updated on the basis of the last transmission opportunities (of order of 50) and eventually the MCS is adapted if the measured PDU-ER is above (or below) an upper (lower) threshold.

When the measured PDU-ER decreases under the lower value, and lasts for at least 50 transmission events, the scheduler changes MCS to a more favorable level. The opposite happens when the PDU-ER is higher than the upper value. The considered PDU-ER is an averaged quantity, which in normal conditions is assumed to vary in the range [0.05-0.6], as adopted for the simulations.

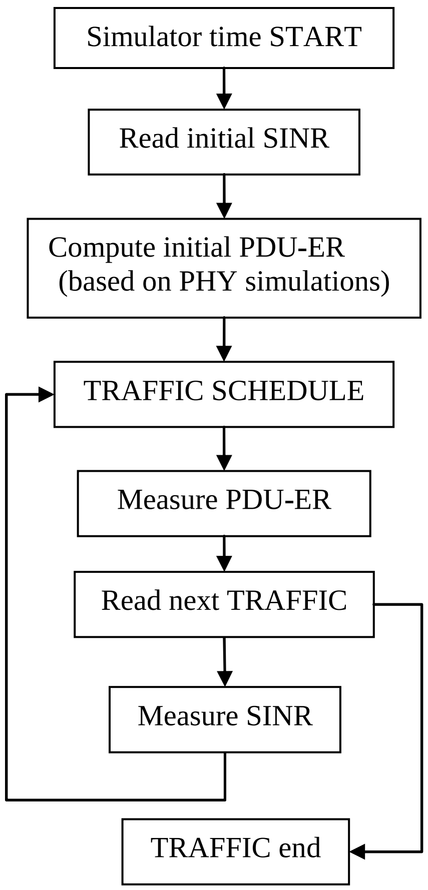


Figure 41: Scheme of the realization of traffic flow for the system simulator.

The scheduler flow described in Figure 41 considers such interval as the threshold values to adapt the MCS scheme: when PDU-ER is below lower limit, the RRM assigns a MCS with higher capacity, while in the opposite case a stronger MCS. Figure 42 shows an example of SNR temporal variation represented for 4 users. The effect over MCS assignment in reported in Figure 43. The frequent changes that appear in this sample run are a consequence of the traffic load and of the abrupt SNR changes which, for this test only, have been set to conditions particularly demanding.

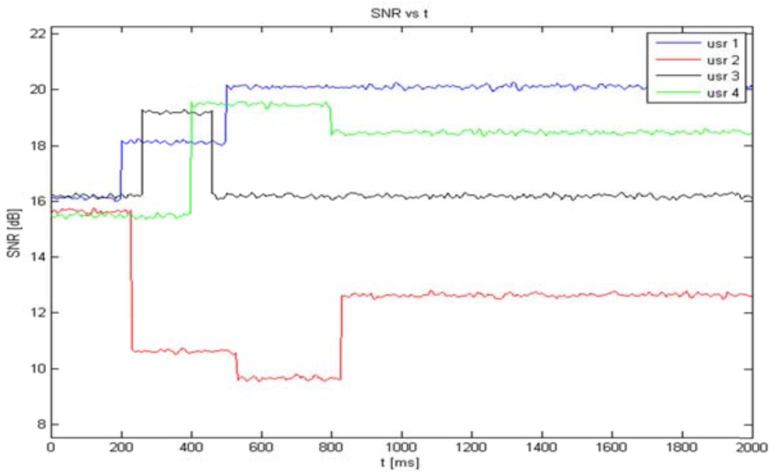


Figure 42. Example of SNR variation for 4 users.

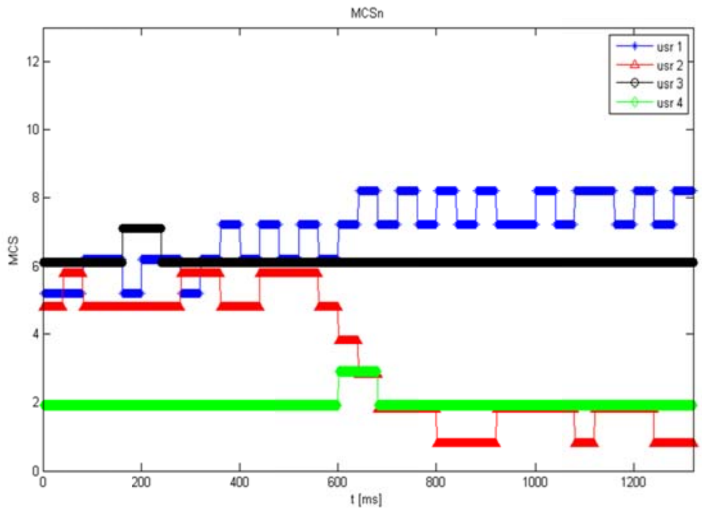


Figure 43. Example of MCS variation for 4 users, corresponding to SNR varying as in Figure 42.

Figure 44 reports the PDU-ER measured over time for the 4 users whose other parameters are shown in Figure 42 and

Figure 43. The PDU-ER value at a certain instant of time is the time average of the instantaneous PDU-ER measured over the last 50 transmission opportunities. The abrupt changes downwards are due to the change to a stronger MCS which reduces PDU-ER well above the upper threshold value, while the blue horizontal lines are fixed to the two thresholds. In this example, there is more activity for the users with a high rate FTP (user 1 and 2), while users 3 and 4 are performing VoIP, with a much less traffic flow, at timescale of ms.

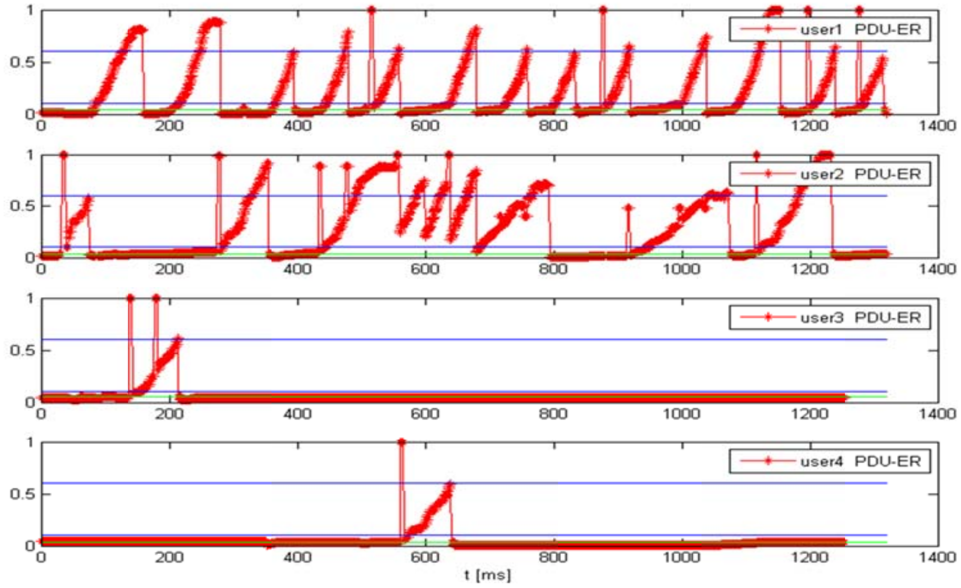


Figure 44: Example of PDU-ER variation for 4 users, corresponding to SNR varying as in Figure 42. Users 1 and 2 run FTP traffic, users 3 and 4 run VoIP.

7.1.4.2 *Scheduler and priorities*

The assignment of radio resources has been designed both for power and frequency assignment. Power allocation has been considered as a parameter which can be set depending on different possible criteria which have in part been considered in Section 6.1.5 of [Freedom-D51] that we recall here for clarity:

- Maximum power, 20 dBm
- Minimum power, 10 dBm
- Target throughput power, assigned on the basis of the desired QoS
- Optimization output, i.e. assigned on the basis of an optimization strategy.

Considering frequency allocation, resources can be assigned by several methods:

- The MBS transmits over the entire licensed band, adapting to frequency selective channels of MUEs.
- Rigid band sharing between Macro and femto network. Interference among the two networks is reduced at the expenses of efficient re-use of resources.
- MBS has a band usage independent of the femto network, while the FAPs implement optimization strategies for interference mitigation.

The PRB texture shown in **Figure 39** is filled by assigning the most favorable frequency interval to each user. The module developed allows emulating all dimensions of LTE PRB standard, from 6 to 100.

At each transmission event, every user receives a score depending on

- current queue length,
- priority of the type of traffic running (e.g., for delay sensitive applications such as VoIP)
- number of past occasions to transmit, which depend both on traffic load and past resources competitions in which that user has been postponed due to a low score.

The higher the score, the higher the priority given a user by the scheduler to allocate a set of packets. Figure 46 shows a snapshot of the priority values for users attached to a MBS. The different colors refer to three types of users on the basis of the number and types of applications running: red, VoIP only; blue, VoIP and FTP; green, add also bursty traffic.

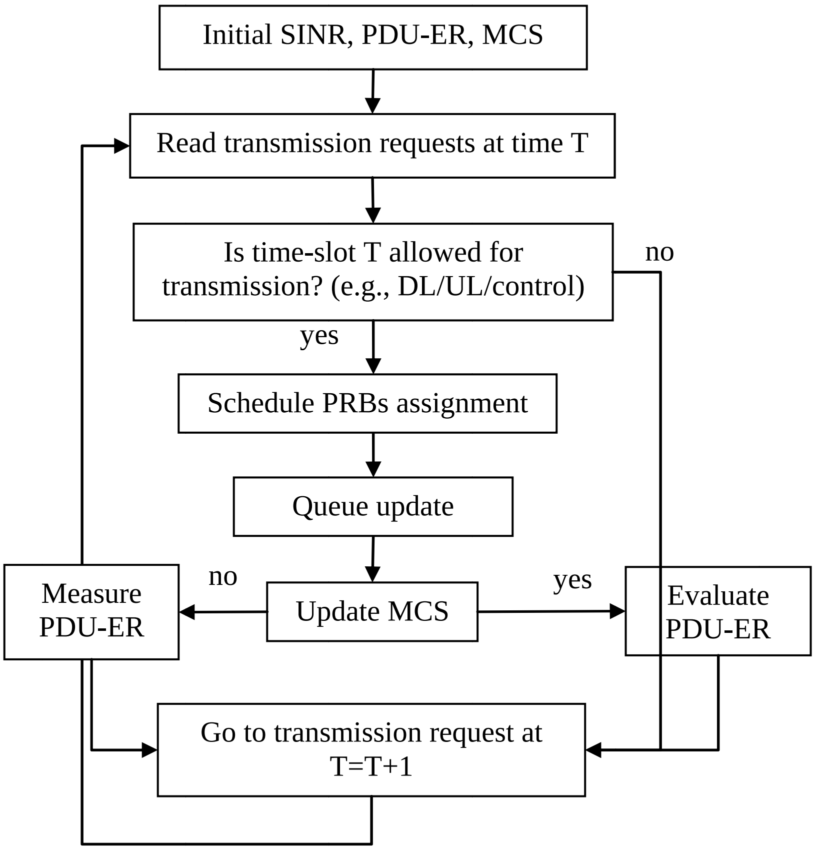


Figure 45: Scheme of the network traffic management.

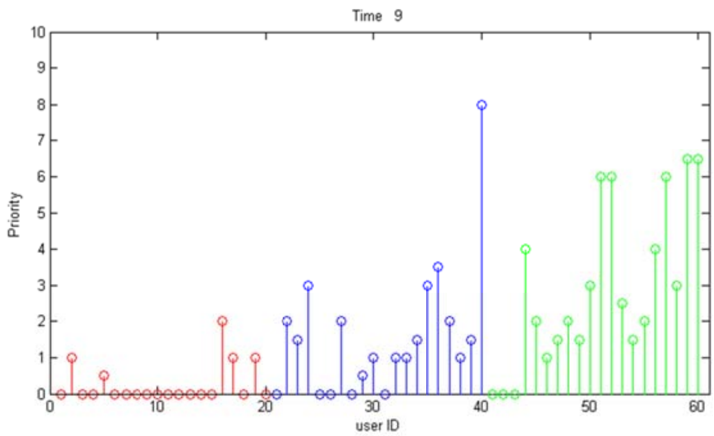


Figure 46: Priority metrics for the scheduler at a fixed time instant. Different colors identify different types of users, on the basis of applications running. Red, VoIP; blue, VoIP and FTP; green, VoIP, FTP, bursty.

Transmission allocations are grouped according to the scheme represented in Figure 47. Once one or more packet is transmitted, the system counts the number of ACKs or NACKs packets (20 byte long) received and eventually reschedules the bad packets at a later instant of time, at least after 3 subframes (i.e., 30 ms from NACK), updating the current queue.

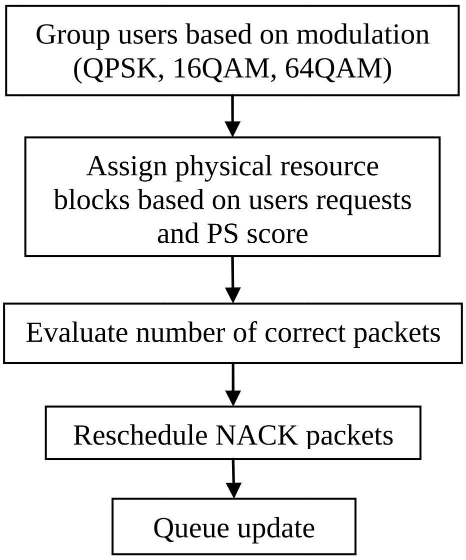


Figure 47: Scheme of PRBs assignment and queue load management.

Figure 48 represents the output of the scheduler for time interval of transmission, shown here on the basis of maximum 25 PRBs for the sake of graphic clarity. The adoption of 100 PRBs would only result in a figure difficult to read. The horizontal axis represents sequence time of allocations, the vertical axis frequency band of PRBs, colors refer to users ID, which in this case are 44. White positions are unassigned frequencies.

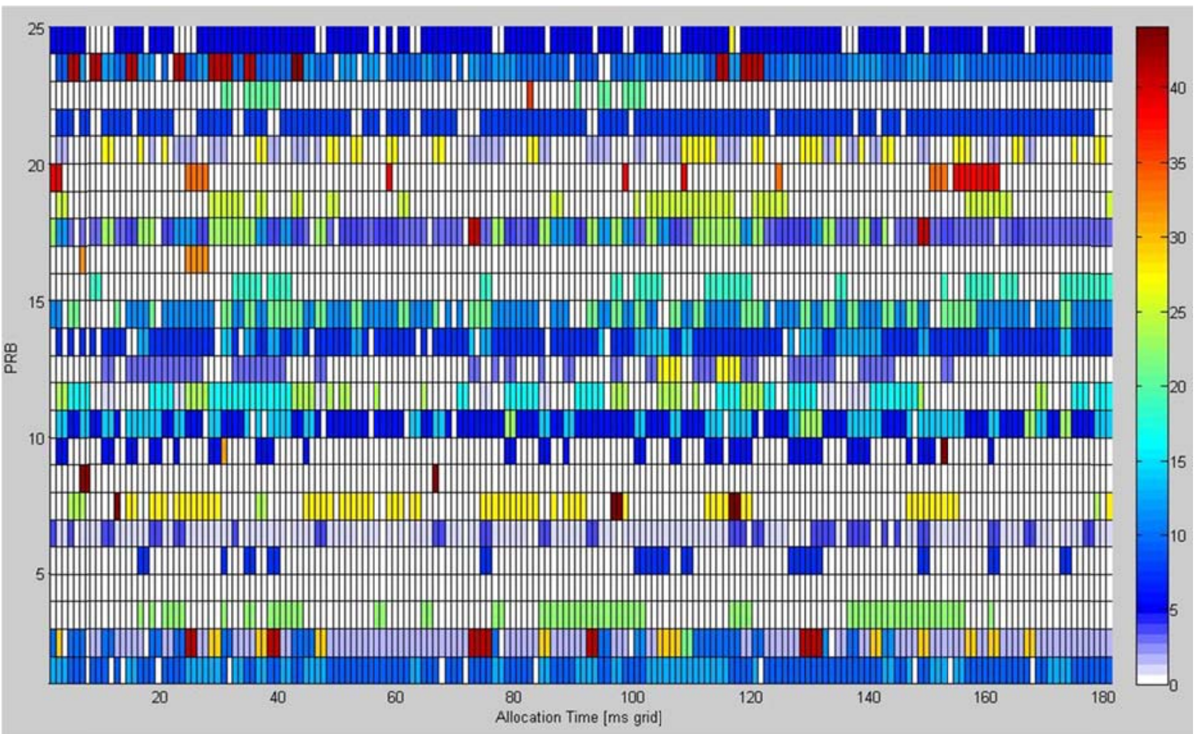


Figure 48: Temporal structure of PRBs allocations for a set of 44 MUEs. Colors correspond to user ID, allocation time must be matched to DL.

7.1.5 UE requirements

User equipment (UE) can have several services (applications) simultaneously active (voice, web browsing, interactive gaming, data transmission, streaming etc.), each with its own QoS requirements such as throughput, latency etc. Every service has its traffic model (see Section 3 of [Freedom-D51]) which constitutes one of the main inputs for the scheduler (see Section 3 of [Freedom-D51]).

UE requirements, in terms of services requested, are reported in WP2 (see [Freedom-D21] for details).

The users deployed in the network have been divided in three possible types, depending on the type and number of services running on the mobile devices:

- Type 1. VoIP traffic only.
- Type 2. VoIP and FTP traffic.
- Type 3. VoIP, FTP and bursty traffic.

In our simulations has been considered on average an equal number of users for the three types.

7.2 System-level and user-level performance

The clustering strategies for a FAP-based network are evaluated from a system level perspective, in terms of network performance and convergence time of the algorithms. The system-level performance of the network has been compared with a network without implementation of interference planning strategies extensively in 5A1 (see [Freedom-D51]). In this Section we will show how, for some topologies of interest, clustering before optimization and running parallel processes provides a significant gain in terms of complexity, convergence time, though getting equivalent results in terms of resources assignment and amount of overhead traffic over the backbone. The performance classes are based on a set of metrics defined to highlight peculiar properties of the system (see Section 6.4). Details about the genetic algorithm terminology and parameters meaning are reported extensively in Section 8 of [Freedom-D32].

7.2.1 GO and ring topology

In this Section are presented the results of the GA applied to different levels of population for clusters composed of 12, 32 and 186 FAPs/FUEs.

The output of the GA providing the power allocation is depicted in Figure 49. The left panel shows the GA result for a single triplet of the ring while the right panel reports the final allocation for all FUEs in the cluster after 15 iterations.

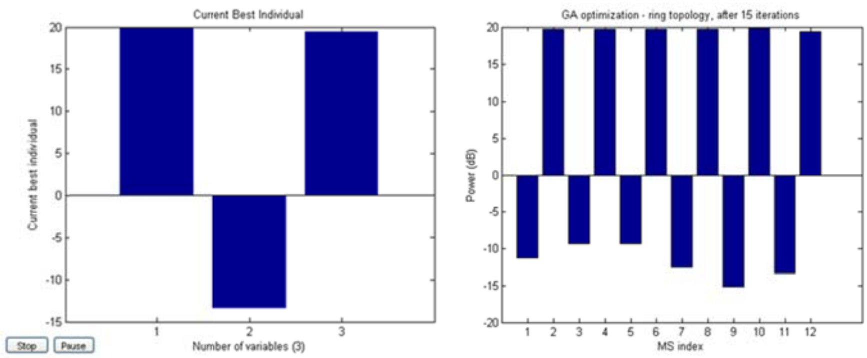


Figure 49. GA output for a system of 12 FUEs with a ring-next topology.

The GA parameters search for a more populated system was applied to rings of several dimensions. In the following figure are reported the cases of 32 and 186 FAPs, whose outputs are plotted in the left panels of Figure 50 and Figure 51, respectively. For both FAPs populations, the right panel of Figure 50, and Figure 52, show the number of *nearby FUEs* whose power allocation is strongly sub-optimal, in the sense that can imply a higher level of interference (both transmitters competing with the same power) or a decrease of transmission power (both transmitters without transmission opportunity). This effect is apparent for the first steps of the GA involving a large number of FAPs and decreases when the process is cycled over the ring after few steps (5 at most in our tests) and offers a mean to set a limit to the number of iterations necessary for the GA convergence over the whole ring.

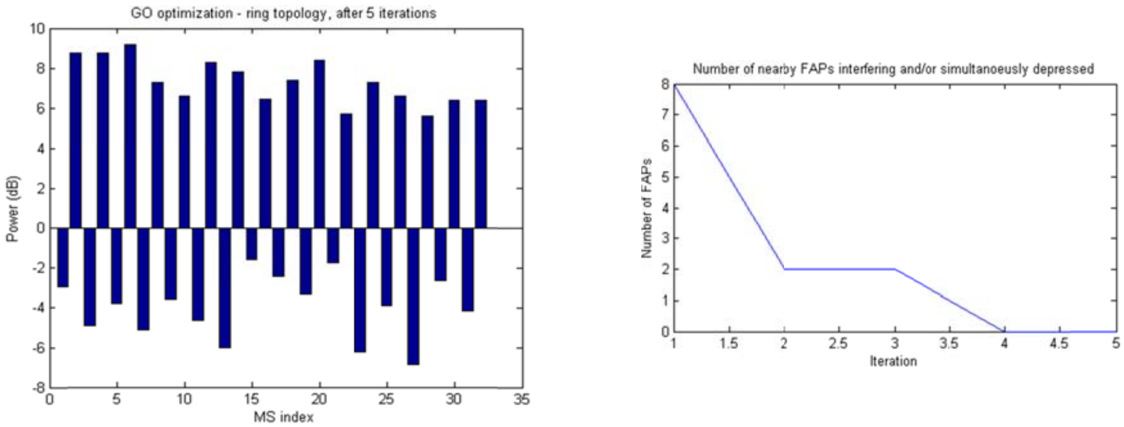


Figure 50. GA output for a system of 32 FUEs with a ring-next topology.

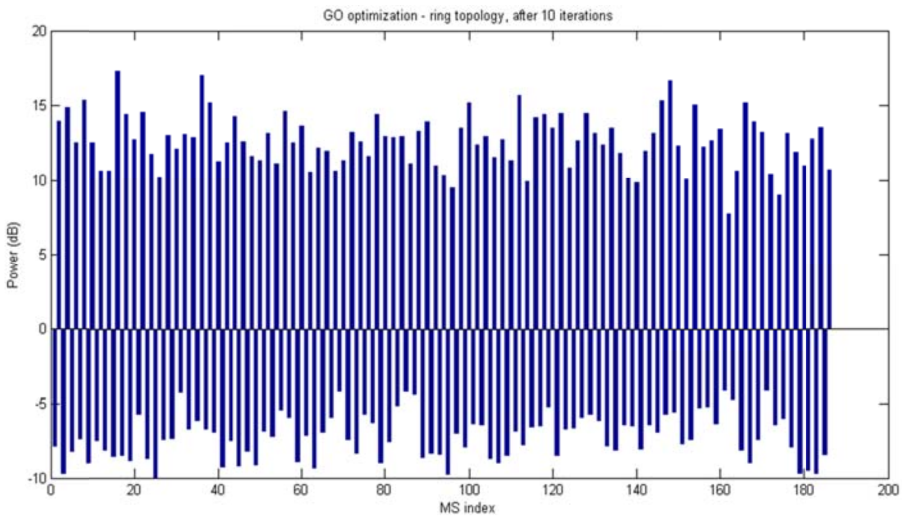


Figure 51. GA output for a system of 186 FUEs with a ring-next topology.

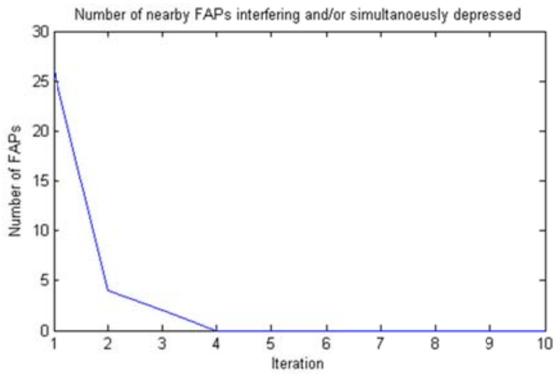


Figure 52. Evaluation of nearby MSs competing for the same resources vs. iteration number for a system of 186 MSs with a ring-next topology.

7.2.2 GO and blocks topology

The GA optimization for the scenario of three blocks is made of three clusters to evaluate its scalability, and has been tested for three populations' sizes with different levels of cross-interference (expressed by the overlap parameter). The output of the GA is as follows:

- Figure 53 shows the case of 5 FUEs per block with an overlap of 2;
- Figure 54 reports 9 FUEs per block with and overlap 3;
- Figure 55 for 19 FUEs per block and overlap 5.

From the GA output in this implementation scheme, one sees that the FUEs at the intersection of two nearby blocks, undergoing the double interference from other FUEs in the same block and from the adjacent one, result always to be depressed by the optimization process.

Finally, it has been verified that the algorithm implemented for a set-up of three blocks of FUEs resembles the one of three independent blocks when the overlap is set to zero, as shown in Figure 56.

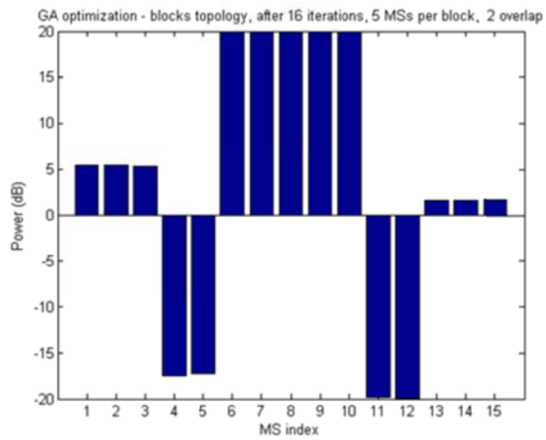


Figure 53. GA optimization. Three blocks, 5 FUEs per block, overlap of 2.

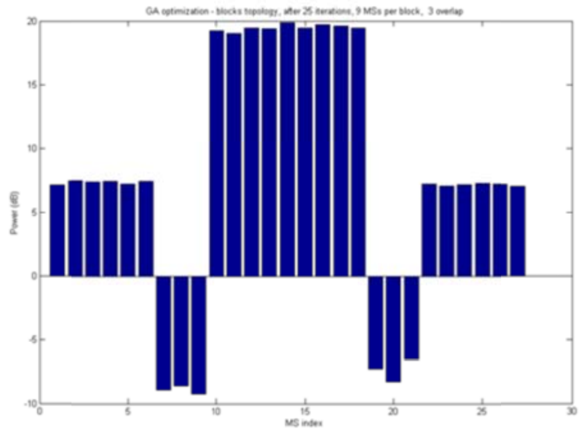


Figure 54. GA optimization. Three blocks, 9 FUEs per block, overlap of 3.

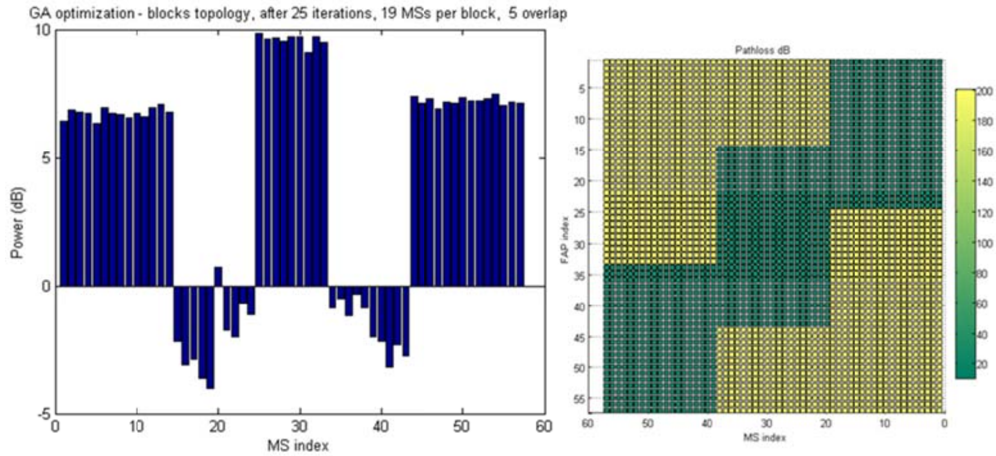


Figure 55. Three blocks, 19 FUEs per block, overlap of 5. Left panel: GA optimization. Right panel: pathloss matrix, in dB.

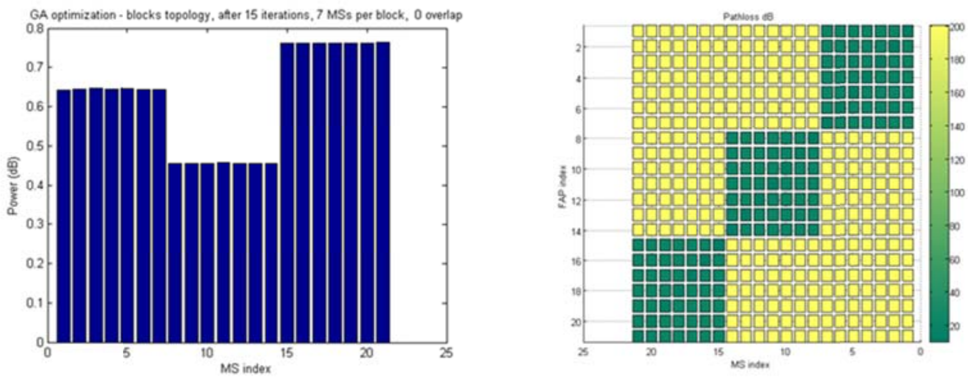


Figure 56. Three blocks, 7 FUEs per block, overlap of 0. Left panel: GA optimization. Right panel: pathloss matrix, in dB.

7.2.3 Comparison of results to the unclustered approach

The comparison of system performances between clustered and unclustered approach has been performed by evaluating resources assignment after GO in both cases, showing how at system level the amount of resources needed is strongly in favour of the clustered scheme. Although an intrinsically sub-optimal parameters such as GO shows small variations in output, the two implementations provide a comparable resources assignment. Table 3 and Table 4 report the parameters' values to get GO convergence for clustered (lines highlighted in grey) vs unclustered (clusters=1) scenarios in some interesting cases for increasing number of FAPs and with different levels of overlap among nearby clusters.

The relevant parameters to get convergence are

- number of iterations *J*, representing the number of times the GO must be run on each cluster after setting the double-valued parameters;
- population *P*, i.e. the number of GA individuals parameterizing the diversity of trial solutions; every individual is a possible solution to be scored by the fitness function or tested by the users;
- generations *G*, i.e. the how many times the GA has to generate new individuals to evaluate the fitness function.

For a clustered system, at each iteration there is an exchange of solutions among the (independent) optimization processes. Population and generations values are directly related to the time necessary to the GO to converge T_c as $T_c = J \text{x} P \text{x} G$. If the processing unit collects only SINRs from all users T_c is expressed in number of frames. On the other hand, if the central unit has knowledge of all transmission pathlosses among transmitters under optimization (for a detailed discussion on this aspect, refer to [Freedom-D32]) T_c reduces to a measurement of complexity for CPU processing time.
The comparison of clustered vs unclusterd implementation shows how clustering reduced of at least one order of magnitude the quantity T_c, and more than 2 orders of magnitude for deployments with clusters including larger number of FAPs.

In real scenarios emerges that clusters are usually composed of less than 20 units and overlap is of order of a few (i.e., 2-10 units), although the topology of the overlaps could include more that 3 nearby blocks.

N Faps	Iterations	Population	Generations	Clusters	Convergence time *T=JxPxG*
12	3	15	5	6	225
	1	40 120	160 110	1	6400 13200
32	4	15	5	16	300
	1	40 120	500 230	1	20000 27600
64	4	15	5	32	300
	1	150 250	550 490	1	82500 122500
186	4	15	5	98	300
	1	250	>700	1	>175000

Table 3: Comparison of optimization performances for clustered vs. not clusterd implementation. Ring topology.

N FAPs	parameters		Iterations	Population	Generations	clusters	Convergence time *T=JxPxG*
30	N FAPs per block N blocks overlap	10 3 3	8	25	10	3	2000
			1	100	230	1	23000
75	N FAPs per block N blocks overlap	25 3 7	10	25	10	3	2500
			1	100	250	1	25000
105	N FAPs per block N blocks overlap	35 3 10	15	25	10	3	6250
			1	100	>400	1	>40000

Table 4: Comparison of optimization performances for clustered vs. not clusterd implementation. Blocks topology.

8 PERFORMANCE EVALUATION

The FAP-based network is analyzed from two different perspectives: network performance (system-level analysis) and user experience (individual UE analysis). The considerations made within this study should take also into account the economical aspect of both solutions.

Analyses of the interference and radio coverage performance, without any specific cooperation or coordination techniques, are reported in Section 8.1, based on the LTE coverage simulator introduced in Section 3.

Analyses in Section 8.1 precede the system-level evaluation of a selected subset of the algorithms studied in activities 3A2 (coordination) and 3A3 (cooperation) of WP3.

The performance analysis will allow evaluating network enhancement solutions and giving some recommendations in function of the deployment type. The task is to answer the following questions:

- Which benefits gets the overall network from the implementation?
- Computing load (iterations, exchange of information, complexity issue) is reduced?
- How clustering affect algorithm efficiency?
- Is it possible to highlight different hierarchies among clusters of users?

The expected results have to assess the efficiency of clustering and interference planning algorithms at system level and their effect on the network architecture. The evaluation of the results will address if the adoption of the proposed strategies provides an enhancement of the overall network performances and if this implies also some cost, for example in terms of user-level performances or fairness.

Comparison of solutions for network simulations implementing clustering criteria with solutions without interference planning will provide recommendations on network implementation, highlighting deployment characteristics when a strategy is particularly performing. Complexity issues will also be addressed.

8.1 Results for interference analysis

8.1.1 Simulation inputs

Network parameters, key aspects of the simulation methodology and simulation parameters are summarized in Table 5 and Table 6 below. See Section 3 for a whole description of the simulation tools and methodology.

The simulation tools does not implement any interference mitigation, therefore outputs expressed as spectral efficiency and capacity outputs must be considered as pessimistic. The simulation tools exploits the MIMO configuration to generate average diversity gain, but do not consider any spatial multiplexing; therefore the maximum LTE spectral efficiency is 5.2bps/Hz.

System	Technology	LTE FDD
	Frequency band	2.0GHz
	Channel bandwidth	2×10MHz
Macro layout (optional)	Sectorisation	Three sectors (or cells) per site
	Macro network design	- Hexagonal site deployment - Two rings around the central site, i.e. 19 sites corresponding to 57 cells
	Environment	- Urban - Suburban
	Inter-site distance (ISD)	- Urban: 500m - Suburban: 1732m
	Average MBS (macro base station) density	- ISD=500m: 4.62 sites/km², 13.86 MBS/km² - ISD=1732m: 0.38 sites/km², 1.15 MBS/km²
	MBS antenna height	32m
	MBS total transmit power	46dBm
	MBS antenna	Directional, 14dBi gain
	MBS antenna elect. down-tilt	- ISD=500m: 6° - ISD=1732m: 2°
	MBS nb antennas	4
Femto layout	Deployment zone	Within the study area shown in Figure 57
	Deployment type	- Urban: in corporate buildings - Suburban: in houses
	Spectrum usage	Co-channel
	Access mode	- Closed - Open
	FAP (femto access point) antenna height	1m above floor
	FAP max transmit power	- 10dBm - 20dBm
	FAP antenna	Omnidirectional, 5dBi gain
	FAP nb antennas	2
User	Indoor / Outdoor distribution	- Indoor: 80% - Outdoor: 20%
	UE antenna height	1.5m
	UE antenna	Omnidirectional, 0dBi
	UE noise figure	9dB

Table 5: Network parameters.

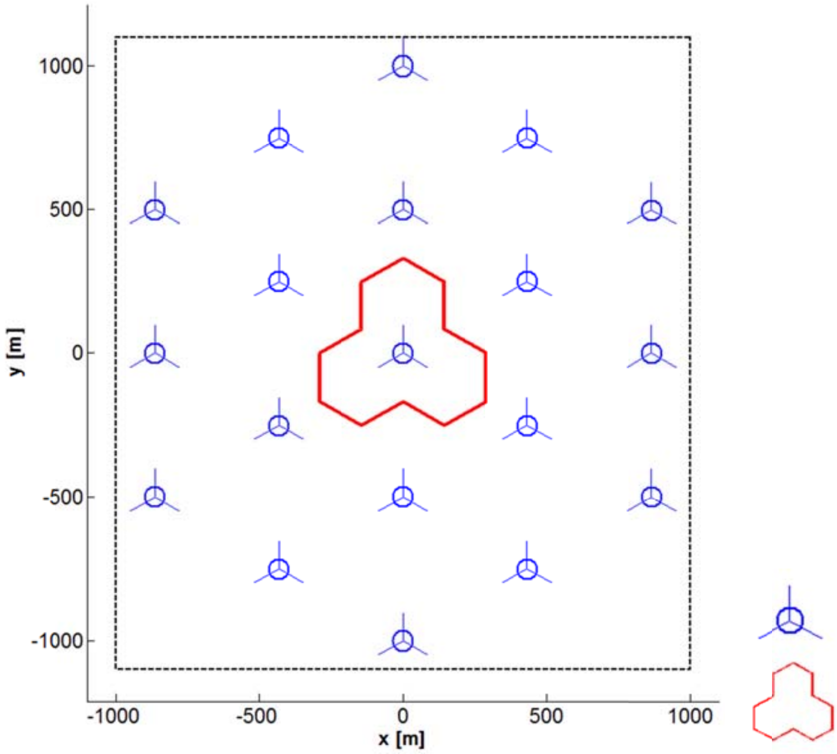


Figure 57. Macro network layout and Study area.

Random FAP deployment	Urban	- Random distribution of FAPs in corporate buildings: - Uniformly -Regularly in staggered rows (see Figure 58) - Non uniformly – distance to exterior wall < 1m - Non uniformly – distance to exterior wall > 5m - At most 1 FAP per 10m×10m small-area
	Suburban	- Random uniform distribution of FAPs in houses - At most one FAP per house
	FAP density	*Variable*
	FAP activation ratio	*Variable*
Path-loss (incl. shadowing)	Synthetic environment	Analytical models defined in [D21] and [D31]
	Real environment	Site-specific models defined in [D21] and [D31]
LTE coverage	Link	DL only
	PHY/MAC layers abstraction	- Random RB allocation - No interference management - No spatial multiplexing, only average diversity gain - Average downlink traffic load (TL) assigned to each MBS or FAP (TL = average percentage of RB's allocated by the cell) - TL for MBS: 50% by default - TL for FAP: *variable*
	Coverage prediction	- Average inter-cell interference calculation - SINR–MCS mapping - 3D (multi-floor) coverage matrices

Table 6: Simulation methodology.

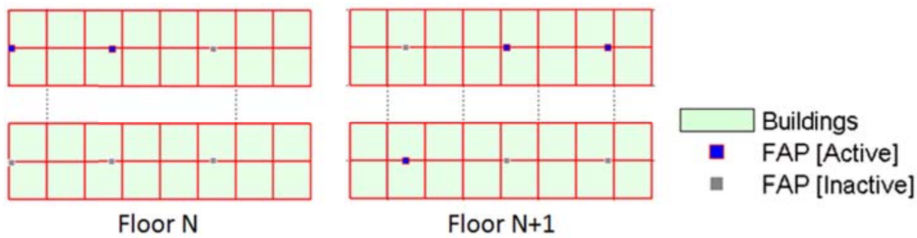


Figure 58. Example of a regular FAP deployment in staggered rows.

8.1.2 Scenarios IA-1 and IA-2 – Impact on local urban corporate coverage

Scenarios IA-1 and IA-2 evaluate the impact of a FAP deployment in one restricted urban corporate area (composed of a few buildings only) in presence of existing macro coverage.

Scenario IA-1 evaluates FAP deployments at the ground-floor of a 20m×60m wide building, whereas in scenario IA-2, FAPs are deployed at all floors of two neighbor buildings of random size (from 20m×40m to 20m×80m).

Several sub-scenarios are investigated from changing the FAP properties and FAP locations given in Table 7. The parameters of the reference scenario highlighted in bold are always applied, unless otherwise mentioned.

Three different types of user are evaluated:

- FAP subscriber, who is located in the same 10m×10m small area as a FAP.
- Corporate FAP subscriber, who is located in the same corporate unit area (whole floor or whole buildings) as the FAPs.
- Non-subscriber, who is not part of any FAP closed subscriber group.

Macro network design	**- ISD = 500m** - ISD = 1732m
Size of a corporate unit **(considering that all FAPs deployed within the surface of a corporate unit own to this single corporate unit)**	**- 10m×10m small area** - One floor - One building
FAP deployment	- Random distribution of FAPs in corporate buildings: - **Uniformly** - Regularly in staggered rows (see Figure 58) - Non uniformly – distance to exterior wall < 1m - Non uniformly – distance to exterior wall > 5m
FAP distance to the MBS	**- Greater than ISD/3** - Inferior to ISD/3
FAP density	**20%** and 50% of 10m×10m small areas 20% density = 0.002 FAP / m² within the floor 50% density = 0.005 FAP / m² within the floor
Traffic in femto layout	- FAP activation ratios **50%** and 100% with TL=10% for active FAP's
FAP Access mode	- Closed - Open
FAP max transmit power	**- 20dBm** - 10dBm

Table 7: Parameters for IA-1 and IA-2 sub-scenarios.

8.1.2.1 *Scenario IA-1 – Impact of a single-floor FAP deployment on network coverage*

The local impact of FAPs on SINR maps may be observed from each random FAP realization. The example in Figure 59 shows SINR maps simulated at the ground-floor of two buildings from one idle FAP and one active FAP deployed at the ground-floor of one of these buildings. The SINR is calculated for a new connecting user who may be located at any pixel in the map, and who is not responsible of the initial FAP activity, i.e. this new user can be connected to the initially idle FAP is this one is the best server.

The indoor SINR for the macro-only network ranges from –2dB to 9dB, whereas the two-tier network SINR significantly increase in open-access mode: up to 65dB in the same 10m×10m small area as a FAP; up to 5dB at 30m indoors. Figure 59 (c) illustrates the SINR levels in presence of closed-access FAPs. Users inside the FAP small areas are assumed to be FAP subscribers: as with open-access FAPs, SINR levels increase by up to 65dB. On the other hand, users outside the FAP small-areas are assumed to be non-subscribers: the SINR levels decrease up to 38dB within 20m around the active FAP. Finally, Figure 59 (d) shows the SINR map for non-subscribers still in presence of closed-access FAPs; the SINR levels decrease up to 54dB in the active FAP small-area.

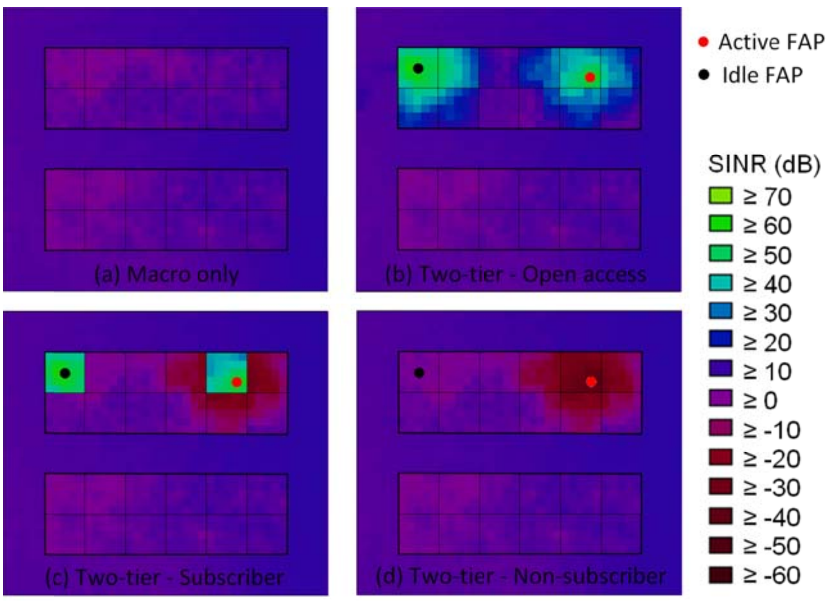


Figure 59. Scenario IA-1 – SINR maps at the deployment floor (ground floor).

Figure 60 shows the SINR maps at the first floor. The SINR levels from the macro-only network have the same range as at ground floor. The SINR levels in the two-tier network in open-access mode increase by up to 36dB in the areas located just above the FAPs. Finally, Figure 60 (c) shows the SINR map for non-subscribers in presence of closed-access FAPs. The SINR levels decrease by up to 38dB in areas located above the active FAP.

Thus, FAPs have a significant impact on the SINR levels experienced by FAP subscribers and non-subscribers, at the same floor but also at neighbor floors. The next subsections deals with the impact observed from the whole random simulation in terms of spectral efficiency distributions.

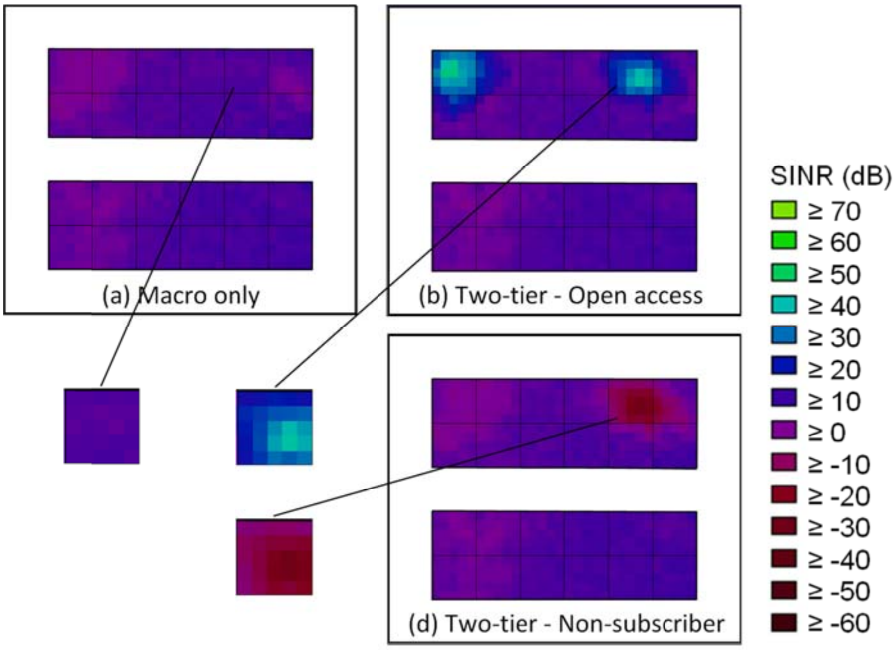


Figure 60. Scenario IA-1 – SINR maps at the first floor.

Firstly, we focus on the impact for FAP subscribers located in the same 10m×10m small area as a FAP.

Figure 61 compares the spectral efficiency CDFs in the macro-only network and in the two-tier network (MBS + FAP) for FAP subscribers. The three cases provide full service coverage but the FAPs enable a tremendous improvement in the coverage quality since the outage probability of the maximum spectral efficiency of the system (5.2bps/Hz) is 10% in closed-access mode and 5% in open-access mode. The difference comes from the fact that, in open-access mode, the user can connect to neighbor FAPs if one of those FAPs becomes its best-server. On the other hand, the macro only network cannot provide such spectral efficiency: 88% outage probability for spectral efficiency higher than 2bps/Hz and 100% above 3.6bps/Hz. Figure 62 provides the comparisons for two additional network configurations: a macro network with an ISD of 1732m and a FAP deployment at short range (<ISD/3) in the reference macro network.

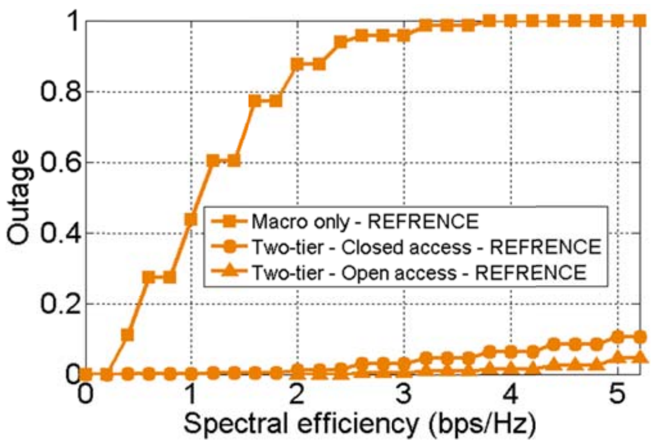


Figure 61. Scenario IA-1 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by a FAP subscriber.

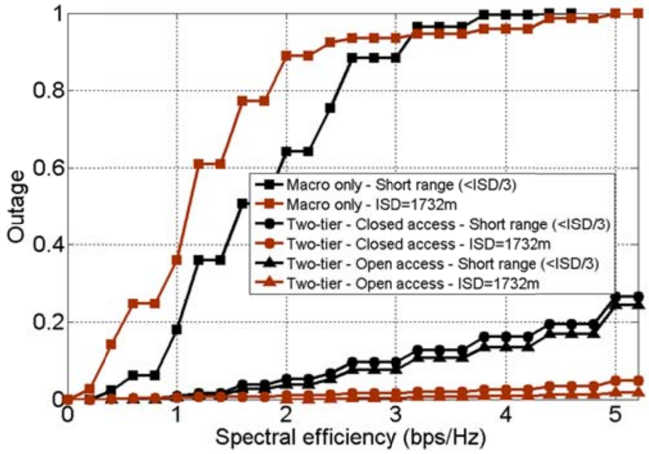


Figure 62. Scenario IA-1 – Impact of network properties on spectral efficiency, as experienced by a FAP subscriber.

Figure 63 illustrates the impact of some FAP properties on the spectral efficiency predicted for FAP subscribers. The benefit is slightly lower when the FAP-to-FAP interference level increases (FAP density=50% or FAP activation ratio=100%) or when the FAP transmit power decreases. The maximum spectral efficiency of the system (5.2bps/Hz) is reached with 5% to 26% outage probability.

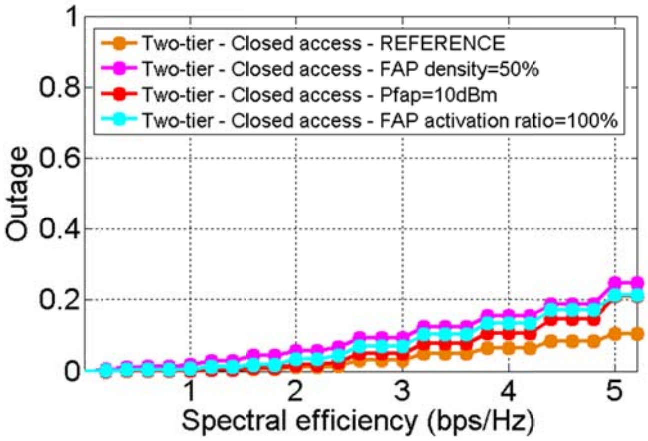


Figure 63. Scenario IA-1 - Impact of FAP properties on spectral efficiency, as experienced by a FAP subscriber.

Secondly, we focus on the impact for corporate FAP subscriber, who is located in the same floor as the FAPs. These results illustrate the performance that should be experienced in two different cases: (1) FAPs are in open-access mode; or (2) FAPs are in closed-access and the predicted user is a subscriber who belongs to the Closed Subscriber Group (CSG) of all FAPs.

Figure 64 illustrates the impact of FAPs on the spectral efficiency CDFs at the whole FAP deployment floor. In the reference scenario, the average spectral efficiency increases by 1bps/Hz and the outage probability of the maximum spectral efficiency (5.2bps/Hz) is 75%. For a macro network with an ISD of 1732m, the spectral efficiency increase is higher since the MBS-to-FAP interference levels are lower. On the opposite, at short range, the spectral efficiency increase is significantly lower since the macro only spectral efficiency is better and the MBS-to-FAP interference levels are higher.

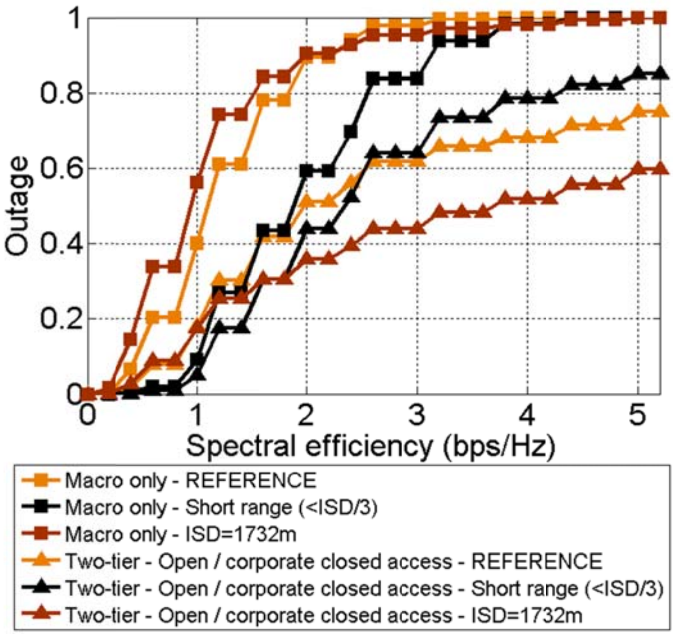


Figure 64. Scenario IA-1 - Spectral efficiency CDFs of macro only and two-tier networks as experienced by a corporate FAP subscriber located at the FAP deployment floor.

Figure 65 shows the impact of some FAP properties on the spectral efficiency:

- Increasing the FAP deployment density from 20% to 50% increases the spectral efficiency by 0.9bps/Hz on average.
- Reducing the FAP transmit power from 20dBm to 10dBm reduces the spectral efficiency by 0.7bps/Hz on average.
- Increasing the FAP activation ratio from 50% to 100% does not have a significant impact on spectral efficiency.

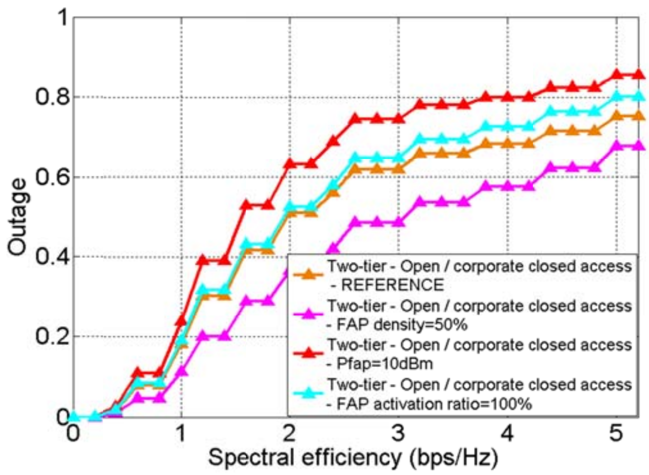


Figure 65. Scenario IA-1 – Impact of FAP properties on spectral efficiency, as experienced by a corporate FAP subscriber located at the FAP deployment floor.

Finally, we focus on the impact of a FAP deployment for non-subscribers. Active FAPs create dead zones (no service coverage) in their whole small areas (10mx10m). Furthermore, Figure 66 gives the impact of FAPs on the spectral efficiency CDFs at the whole FAP deployment floor. In the reference scenario, a dead zone of 20% of the deployment floor is observed and the average spectral efficiency slightly decreases. The dead zone surface is 30% for ISD=1732m and 10% at short range since the MBS signal levels are respectively lower and greater than in the reference scenario.

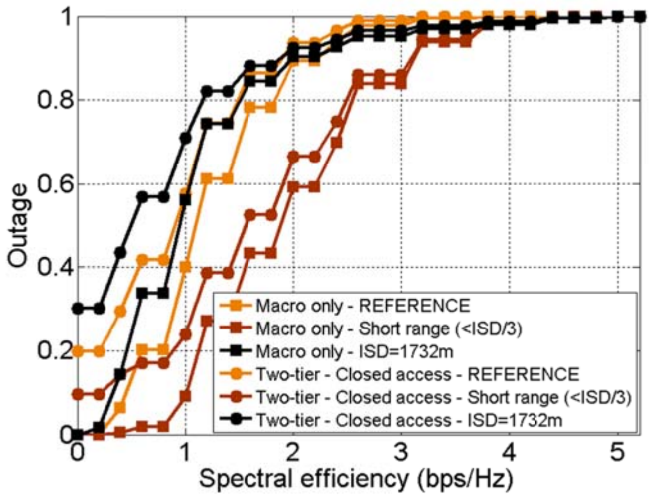


Figure 66. Scenario IA-1 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by a non-subscriber located at the FAP deployment floor.

Figure 67 shows the impact of some FAP properties for non-subscribers located at the deployment floor:

- Increasing the FAP deployment density from 20% to 50% increases the dead zone from 20% to 42%.
- Reducing the FAP transmit power from 20dBm to 10dBm reduces the dead zone to 13%.
- Increasing the FAP activation ratio from 50% to 100% increases the dead zone to 35%.

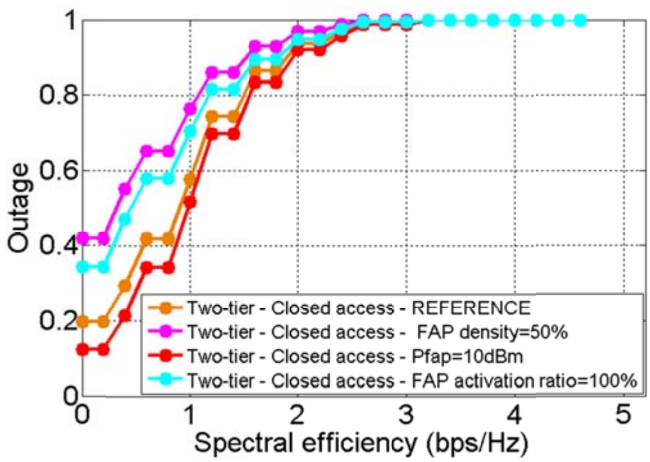


Figure 67. Scenario IA-1 – Impact of FAP properties on spectral efficiency, as experienced by a non-subscriber located at the FAP deployment floor.

8.1.2.2 *Scenario IA-2 – Impact of a building FAP deployment on network coverage*

Firstly, we focus on the impact for FAP subscribers. Figure 68 compares the spectral efficiency CDFs in the macro-only network and in the two-tier network for FAP subscribers for the reference macro network and for a macro network with an ISD of 1732m. Both cases provide full service coverage but the FAPs enable a tremendous improvement in the coverage quality since the outage probability of the maximum spectral efficiency of the system (5.2bps/Hz) is 7% in closed-access mode and 4% in open-access mode. The difference comes from the fact that, in open-access mode, the user can connect to neighbor FAPs if one of those FAPs becomes its best-server. On the other hand, the macro only network cannot provide such spectral efficiency: 92% outage probability for spectral efficiency higher than 2bps/Hz and 100% above 3.6bps/Hz in the reference scenario.

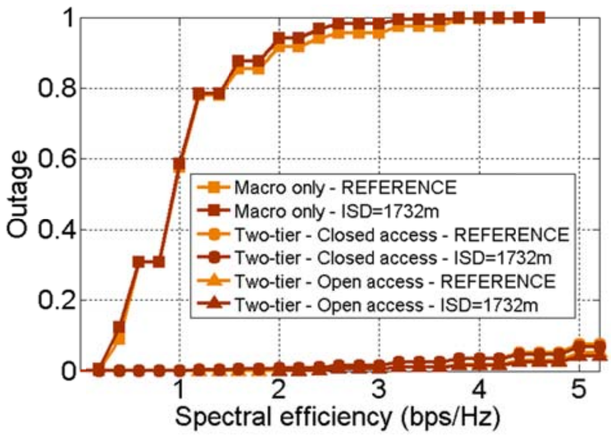


Figure 68. Scenario IA-2 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by a FAP subscriber.

Figure 69 illustrates the impact of some FAP properties on the spectral efficiency predicted for FAP subscribers. The benefit is barely lower when the FAP-to-FAP interference level increases (FAP density=50% or FAP activation ratio=100%) or when the FAP transmit power decreases: the maximum spectral efficiency of the system (5.2bps/Hz) is reached with 7% to 16% outage probability.

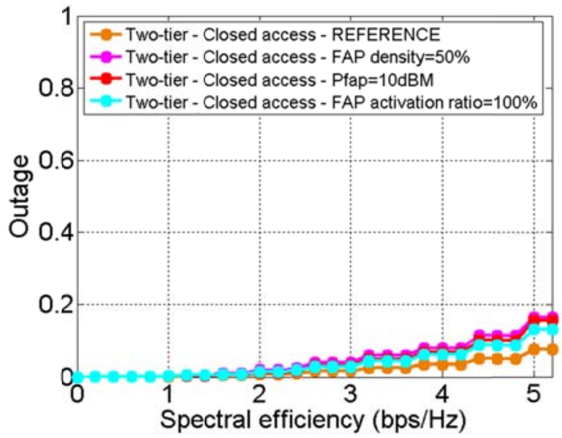


Figure 69. Scenario IA-2 - Impact of FAP properties on spectral efficiency, as experienced by a FAP subscriber.

Figure 70 illustrates the impact of FAP locations. The spectral efficiency distributions are barely the same inside FAP areas. FAP deployment in staggered rows provides a slightly better spectral efficiency since the FAP-to-FAP interference is lowered: the maximum spectral efficiency of the system (5.2bps/Hz) is reached with 3% outage probability against 7% for other FAP locations.

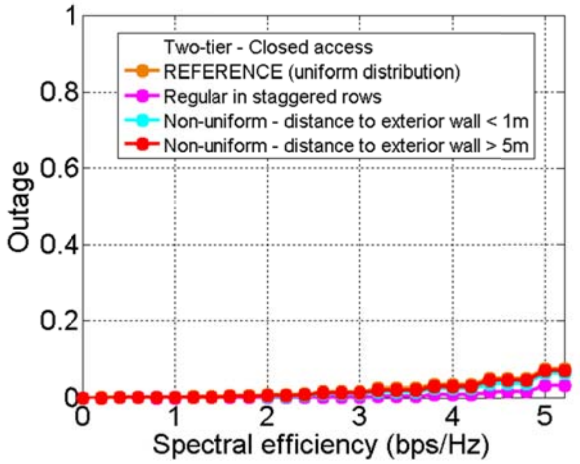


Figure 70. Scenario IA-2 - Impact of FAP locations on spectral efficiency, as experienced by a FAP subscriber.

Secondly, we focus on the impact for corporate FAP subscriber, who is located in the same buildings as the FAPs or in the surrounding streets. These results illustrate the performance that should be experienced in two different cases: (1) FAPs are in open-access mode; or (2) FAPs are in closed-access and the predicted user is a subscriber who belongs to the Closed Subscriber Group (CSG) of all FAPs.

Figure 71 illustrates the impact of FAPs on the spectral efficiency CDFs in the whole building. In the reference scenario, the average spectral efficiency increases by 3bps/Hz, reaching 4.1bps/Hz and the outage probability of the maximum spectral efficiency (5.2bps/Hz) is 61%. For a macro network with an ISD of 1732m, the spectral efficiency increase is higher since the MBS-to-FAP interference levels are lower.

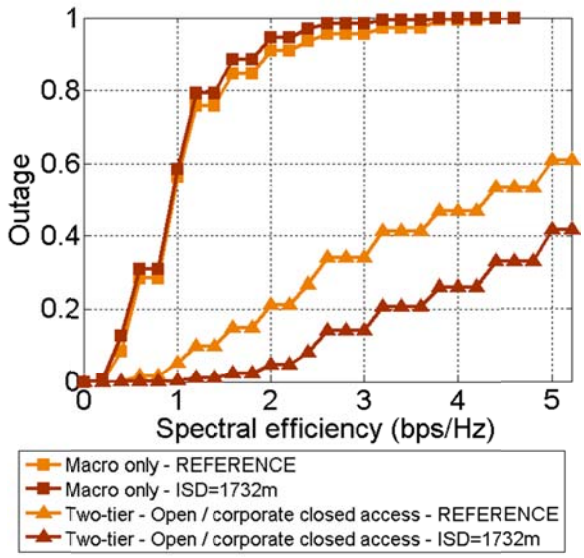


Figure 71. Scenario IA-2 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by a corporate FAP subscriber located in the FAP deployment buildings.

Figure 72 shows the impact of some FAP properties on the spectral efficiency:

- Increasing the FAP deployment density from 20% to 50% decreases the outage probability of the maximum spectral efficiency (5.2bps/Hz) from 60% to 43%.

- Reducing the FAP transmit power from 20dBm to 10dBm increases the outage probability of the maximum spectral efficiency (5.2bps/Hz) from 60% to 76% and reduces the spectral efficiency by 1.7bps/Hz on average.
- Increasing the FAP activation ratio from 50% to 100% increases the outage probability of the maximum spectral efficiency (5.2bps/Hz) from 60% to 95% and reduces the spectral efficiency by 2.2bps/Hz on average.

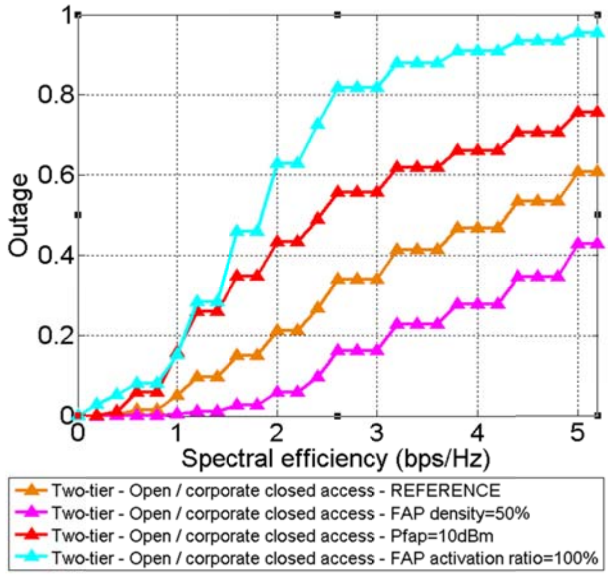


Figure 72. Scenario IA-2 – Impact of FAP properties on spectral efficiency, as experienced by a corporate FAP subscriber located in the FAP deployment buildings.

Figure 73 shows the impact of FAP locations on the spectral efficiency in the FAP deployment buildings, as experienced by a corporate FAP subscriber:

- Regular FAP deployment in staggered rows offers the best spectral efficiency: 53% outage probability for the maximum spectral efficiency (5.2bps/Hz) compared to 60% for the reference scenario (uniform distribution).
- FAP deployment with a distance to the exterior wall lower than 1m offers a slightly decreased spectral efficiency (66% outage probability for the maximum spectral efficiency).
- FAP deployment with a distance to the exterior wall greater than 5m offers barely the same spectral efficiency as in reference scenario (58% outage probability for the maximum spectral efficiency).

Figure 74 shows the impact of FAP locations on the spectral efficiency in the surrounding streets of the FAP deployment buildings, as experienced by a corporate FAP subscriber:

- Regular FAP deployment in staggered rows offers a slightly decreased spectral efficiency than in the reference scenario: 1.4bps/Hz against 1.8bps/Hz on average.
- FAP deployment with a distance to the exterior wall lower than 1m offers a better spectral efficiency than in the reference scenario: 2.3bps/Hz against 1.8bps/Hz on average.
- FAP deployment with a distance to the exterior wall greater than 5m offers a slightly decreased spectral efficiency than in the reference scenario: 1.5bps/Hz against 1.8bps/Hz on average.

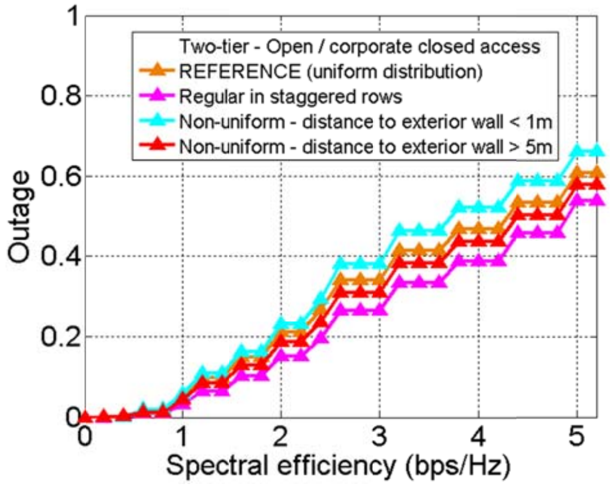


Figure 73. Scenario IA-2 – Impact of FAP locations on spectral efficiency, as experienced by a corporate FAP subscriber located in the FAP deployment buildings.

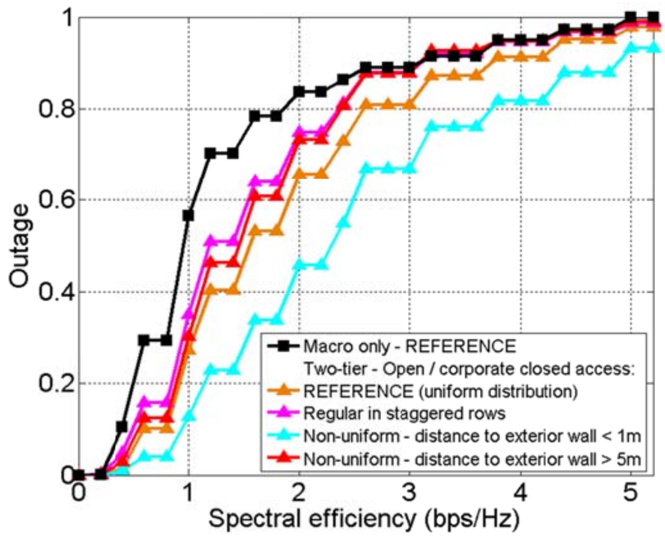


Figure 74. Scenario IA-2 – Impact of FAP properties on spectral efficiency, as experienced by a corporate FAP subscriber located in the surrounding streets of the FAP deployment buildings.

Finally, let us focus on the impact of a FAP deployment on non-subscribers. In closed-access mode, the service coverage is fully deteriorated inside active FAP areas. Figure 75 gives the impact of FAPs on the spectral efficiency CDFs in the whole FAP deployment building. In closed-access mode, 46% of the FAP deployment buildings is not covered, whereas in open-access mode the average spectral efficiency increases by 3bps/Hz and the outage probability of the maximum spectral efficiency is 61% (see Figure 71). The impact of the FAP deployment is much larger than in scenario IA-1 (see Figure 66) since FAPs are deployed at all floors.

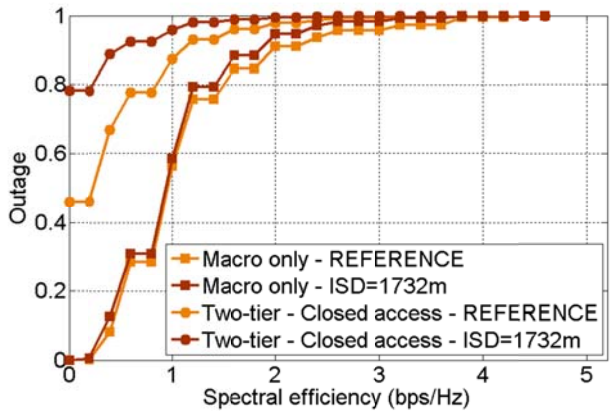


Figure 75. Scenario IA-2 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by a non-subscriber located in the FAP deployment buildings.

Figure 76 shows the impact of some FAP properties for non-subscribers located in the FAP deployment building:

- Increasing the FAP deployment density from 20% to 50% increases the dead zone from 46% to 76%.
- Reducing the FAP transmit power from 20dBm to 10dBm reduces the dead zone to 24%.
- Increasing the FAP activation ratio from 50% to 100% increases the dead zone to 72%.

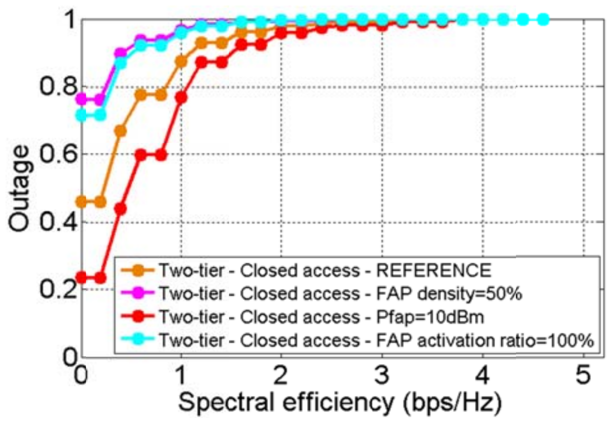


Figure 76. Scenario IA-2 – Impact of FAP properties on spectral efficiency, as experienced by a non-subscriber located in the FAP deployment buildings.

Figure 81 shows the spectral efficiency CDFs in the FAP deployment buildings, as experienced by a non-subscriber, for different FAP locations. The impact of FAPs is barely the same for considered locations: a dead zone of 45%-50% for non-subscriber.

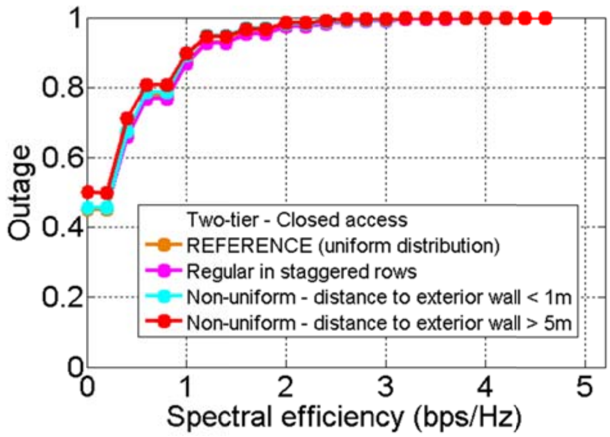


Figure 77. Scenario IA-2 – Impact of FAP locations on spectral efficiency, as experienced by a non-subscriber located in the FAP deployment buildings.

Figure 78 shows the impact of FAP locations on the spectral efficiency in the surrounding streets of the FAP deployment buildings, as experienced by a non-subscriber:

- In the reference scenario, a 10% dead zone is observed.
- Regular FAP deployment in staggered rows reduces the dead zone to 4%.
- FAP deployment with a distance to the exterior wall lower than 1m increases the dead zone to 27%.
- FAP deployment with a distance to the exterior wall greater than 5m reduces the dead zone to 5%.

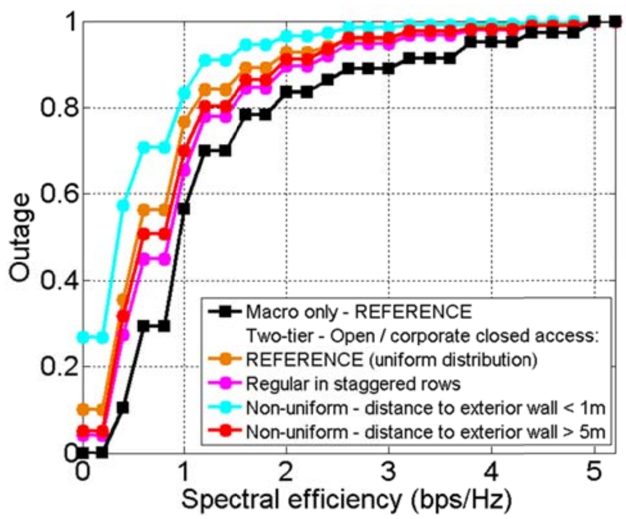


Figure 78. Scenario IA-2 – Impact of FAP locations on spectral efficiency, as experienced by a non-subscriber located in the surrounding streets of the FAP deployment buildings.

8.1.3 Scenario IA-3 – Impact on urban network coverage

Scenario IA-3 evaluates the impact of a dense corporate FAP deployment in an urban network. Large-scale analyses are performed in both synthetic and real environments.

8.1.3.1 *Initial simulations from both real and synthetic environments*

The same scenario described above is simulated in both synthetic and real environments (see section 2). Simulations in real environments use site-specific models [FREEDOM-D21] and 3D vector map data that represents the downtown area of a European large city.

Macro network design	- ISD = 500m
FAP density	- Corporate ratio within the study area (i.e. ratio between corporate buildings and all buildings): 20% - FAP density within corporate buildings: 20%.
FAP properties	- Transmit power: 20dBm.
Traffic in femto layout	- FAP activation ratio: 50% - TL for active FAP's = 10%
FAP access mode	- Open - Closed

Table 8: Scenario IA-3 – Simulation parameters used in both real and synthetic environments.

Figure 79 and Figure 80 show the spectral efficiency CDFs obtained from simulation in synthetic and real environments for respectively an indoor non-subscriber and an outdoor non-subscriber. For the two-tier network, CDFs are given in both open and closed access modes. Significant differences are observed in the macro only network, especially for an outdoor user. It leads to large differences in the two-tier network as well.

Main explanation is that the SIRADEL site-specific propagation models used in real environment provides much higher inter-cell interference in the vicinity of the macro base-stations. This is the result of a long experience in model tuning based on several benchmarks in operational 2G and 3G networks. In particular, the model tuning takes into account the interaction between the antenna pattern and the angular signal dispersion at the base-station.
Such adjustment is not present in the analytical path-loss model used in synthetic environments.
It is decided to continue IA-3 study with real environment only, as this is the one providing the most realistic results.

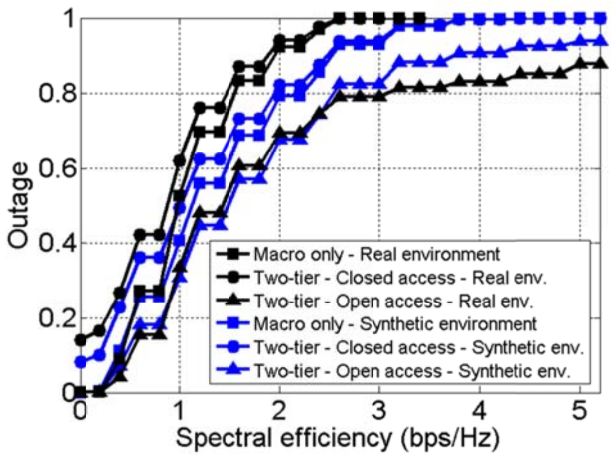


Figure 79. Scenario IA-3 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by an indoor non-subscriber – in real and synthetic environments.

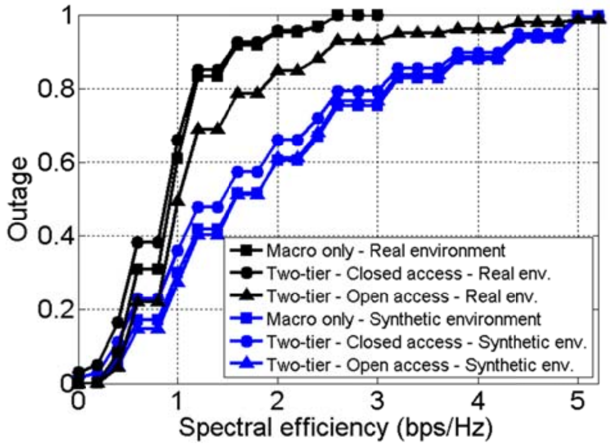


Figure 80. Scenario IA-3 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by an outdoor non-subscriber – in real and synthetic environments.

Remark the difference between analytical and site-specific path-loss models is not as large in suburban areas (especially because the angular dispersion at the base-station is significantly lower). The use of analytical models in IA-4 suburban scenarios, as presented in section 0, is thus perfectly relevant.

8.1.3.2 *Impact of FAP properties on spectral efficiency distribution*

Figure 81 shows the spectral efficiency CDFs of the macro only network and of the two-tier network for an indoor non-subscriber. It illustrates the strong impact of FAPs in the reference scenario (described in Table 8) on spectral efficiency: In open access-mode, 5.2bps/Hz is reached with 85% outage probability compared to 1.8bps/Hz in the macro only network. In closed access-mode, a dead zone of 14% is observed. Besides, reducing the FAP activation ratio from 50% to 10% reduces the dead zone to 3% in closed access-mode. In open access-mode, the spectral efficiency distribution is not really impacted. A third sub-scenario with 10% FAP activation ratio and 50% traffic load gives the same results as the second sub-scenario.

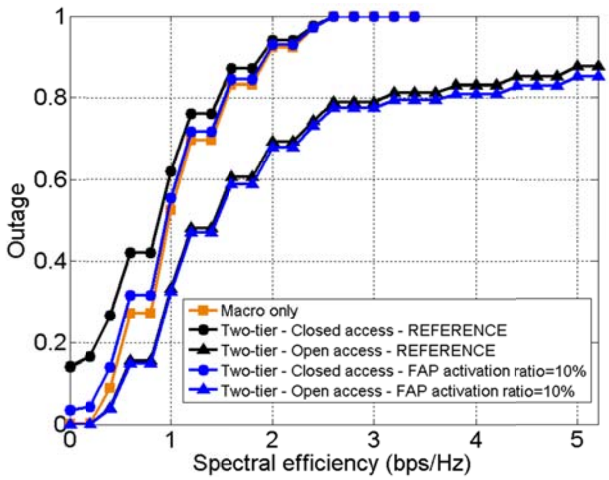


Figure 81. Scenario IA-3 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by an indoor user.

Scenario IA-3 is further exploited for throughput and macro-offload assessment. As these additional outcomes have mainly been generated for business model study, they are summarized in section 9.2.3.

8.1.4 Scenario IA-4 – Impact on suburban network coverage

Scenario IA-4 evaluates the impact of a FAP deployment in residential areas in presence of existing macro coverage. Simulations are conducted in synthetic environment.

Several sub-scenarios are investigated from changing the parameters given in Table 9. The parameters of the reference scenario highlighted in bold are always applied, unless otherwise mentioned.

Macro network design	- ISD = 1732m
FAP density	- Density of houses with network subscribers: 123 house/km^2 - FAP deployment probability in a house: 50%
FAP properties	- Transmit power: 20dBm
Traffic in femto layout	- FAP activation ratio: 10%, 25% and **50%** - TL for active FAP's = **10%** , 30% and 50%
FAP access mode	- Open - Closed

Table 9: Scenario IA-4 – Simulation parameters.

A first result is the evolution of outage probability against spectral efficiency according to FAP traffic load.

Figure 82 compares the spectral efficiency CDFs in both the macro-only network and the two-tier network for an indoor user located in a house with a FAP, considering deployments in closed- or open-access mode.

Note the large increase in spectral efficiency for a subscriber in closed-access mode (5.2bps/Hz with 2% outage) or for any user in open-access mode. Note also the large reduction of the service area for non-subscribers in closed-access mode (i.e. macro deadzone). Service is available in less than 38% of the house surface. Increasing traffic load from 10% to 30% and 50% reduces the service area to 32% and 30% of the house surface respectively.

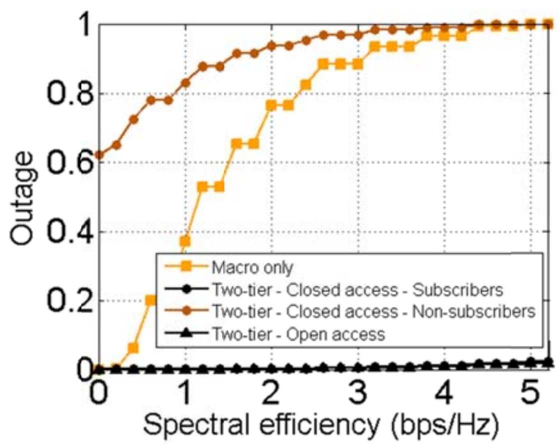


Figure 82. Scenario IA-4 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by an indoor user in FAP area

Figure 83 gives similar result but for an indoor user located in a house without any FAP. These users can take advantage of open-access FAP coverage from FAPs deployed in neighbor houses. Outage probability for spectral efficiency 3.0bps/Hz decreases from 89% in the macro-only network to 61% when traffic load is 10%. It decreases only to 72% when the traffic load is 50% (because of additional interference. Besides, the impact of closed-access mode FAPs makes the indoor service area percentage decrease from 100% to respectively 79% and 63% (see Table 10).

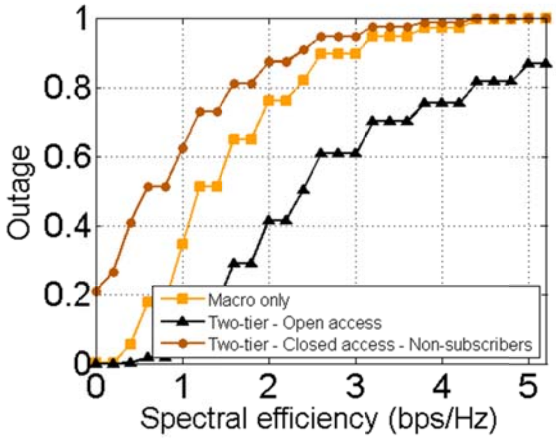


Figure 83. Scenario IA-4 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by an indoor user in houses without FAP.

Outage probabilities of spectral efficiency
- for an indoor user located in the same 12m*12m area as the FAP
- considering a FAP activation ratio of 50%

	0.2 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
Macro only	0%	35%	89%	100%
Open-access mode				
DL traffic load = 10%	0%	7%	61%	87%
DL traffic load = 30%	0%	13%	69%	90%
DL traffic load = 50%	0%	18%	72%	91%
Closed-access mode - Non-Subscribers				
DL traffic load = 10%	21%	62%	95%	100%
DL traffic load = 30%	29%	70%	96%	100%
DL traffic load = 50%	37%	74%	96%	100%

Table 10: Scenarios IA-4 – Macro only and two-tier network outage probabilities according to FAP traffic load for an indoor user located in a house without any FAP.

Figure 84 shows the outdoor (i.e. in-street) spectral efficiency CDFs of the macro only network and the two-tier network. In closed access mode FAPs behave only as interferers, thus the outage probability increases; i.e. the 3bps/Hz spectral efficiency increase from 71% in the macro-only network to 76%. In open-access mode, the outage probability decrease significantly, but the decrease strongly depend on the FAP traffic load. Table 11 gives additional results for a traffic load of 30%.

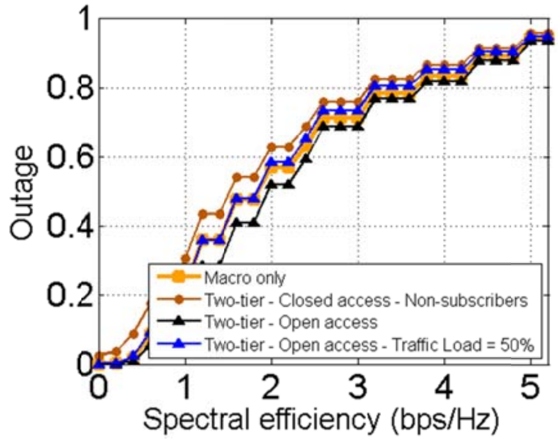


Figure 84. Scenario IA-4 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by an outdoor (in-street) user.

Outage probabilities of spectral efficiency
- for an outdoor user located in street
- considering a FAP activation ratio of 50%

	0.2 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
Macro only	0%	22%	71%	94%
Open-access mode				
DL traffic load = 10%	0%	16%	68%	93%
DL traffic load = 30%	0%	19%	72%	94%
DL traffic load = 50%	0%	22%	73%	95%

Table 11: Scenarios IA-4 – Macro only and two-tier network outage probabilities according to FAP traffic load for an outdoor (in-street) user.

Figure 85 shows the spectral efficiency CDFs outside in the house lot where a FAP is installed. For FAP subscribers in closed-access mode, the outage probability significantly decreases from 94% in the macro-only network to 68% at 3bps/Hz spectral efficiency. In open-access mode, users can take advantage of FAP coverage from FAPs deployed in neighbor houses. Table 12 gives additional results for traffic loads of 30% and 50%.

Second result is the evolution of outage probability as a function of the activation ratio, as shown in Figure 86. The macro indoor dead-zone surface percentage reaches respectively 62%, 34% and 15% for activation ratios 50%, 25% and 10%.

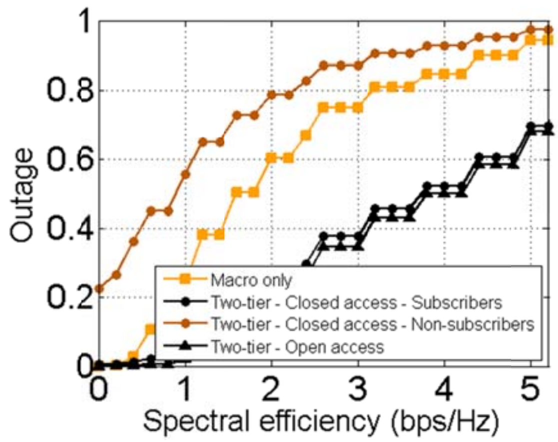


Figure 85. Scenario IA-4 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by an outdoor user located outside in its house lot.

Outage probabilities of spectral efficiency
- for an outdoor user located outside in its house lot
- considering a FAP activation ratio of 50%

	0.2 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
Macro only	0%	23%	73%	94%
Open-access mode				
DL traffic load = 10%	0%	2%	31%	66%
DL traffic load = 30%	0%	2%	35%	68%
DL traffic load = 50%	0%	5%	40%	72%
Closed-access mode - Subscribers				
DL traffic load = 10%	0%	4%	33%	68%
DL traffic load = 30%	0%	5%	38%	70%
DL traffic load = 50%	1%	10%	44%	73%

Table 12: Scenarios IA-4 – Macro only and two-tier network outage probabilities according to FAP traffic load for an outdoor user located outside in its house lot.

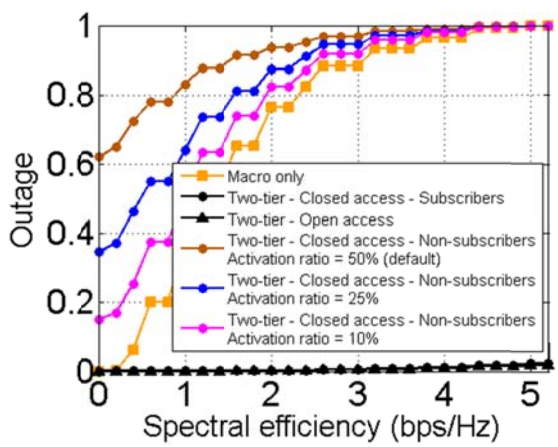


Figure 86. Scenario IA-4 - Spectral efficiency CDFs of macro only and two-tier networks, as experienced by an indoor user in FAP area for different FAP activation ratios.

The impact of FAP activation ratio in both closed and open-access modes for outdoor users with constant traffic load (10%) are summarized in Table 13. As expected, higher activation ratios increase the interference levels, thus leads to coverage performance degradation. This degradation is higher in closed-access mode.

Outage probabilities of spectral efficiency - for an outdoor user located in street - considering a FAP traffic load of 10%				
	0.2 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
Macro only	0%	22%	71%	94%
Open-access mode				
Activation ratio = 10%	0%	14%	65%	92%
Activation ratio = 25%	0%	15%	66%	93%
Activation ratio = 50%	0%	16%	68%	93%
Closed-access mode - Non-Subscribers				
Activation ratio = 10%	0%	24%	72%	95%
Activation ratio = 25%	0%	26%	74%	95%
Activation ratio = 50%	2%	30%	76%	95%

Table 13: Scenarios IA-4 – Macro only and two-tier network outage probabilities according to activation ratio for an outdoor non-subscriber (in-street).

Third result is the evolution of the spectral efficiency according to subscriber house density, considering similar FAP density (50%), FAP traffic load (10% or 50%) and FAP activation ratio (50%).

For outdoor users with FAP closed-access mode deployment:

- FAP traffic load = 10%: dead-zone surface increases from 2% with 123 subscriber house/km² to 7% with 360 subscriber house/km².
- FAP traffic load = 50%: dead-zone surface increases from 7% with 123 subscriber house/km² to 19% with 360 subscriber house/km².

For outdoor users with FAP open-mode deployment:

- FAP traffic load = 10%: the average gain on spectral efficiency is 0.2bps/Hz with 123 subscriber house/km² and 0.4bps/Hz with 360 subscriber house/km².
- FAP traffic load = 50%: no visible gain whatever the subscriber house density is.

8.1.5 Scenarios IA-5 and IA-6 – FAP coverage in urban corporate area (no initial macro coverage)

Scenarios IA-5 and IA-6 evaluate the impact of a FAP deployment in one restricted urban corporate area (composed of a few buildings only) in absence of any macro coverage. They are the same as scenarios IA-1 and IA-2, except that MBS are not taken into account. Thus, refer to section 8.1.2 for scenarios details.

Two different types of user are evaluated:

- FAP subscriber, who is located in the same 10m×10m small area as a FAP.
- Corporate FAP subscriber, who is located in the same corporate unit area (whole floor or whole buildings) as the FAPs.

8.1.5.1 *Scenario IA-5 – Spectral efficiency of a single-floor FAP deployment*

Firstly, we focus on the impact for FAP subscribers located in the same 10m×10m small area as a FAP. Figure 87 compares the spectral efficiency CDFs in the two-tier network: the outage probability of the maximum spectral efficiency of the system (5.2bps/Hz) is 10% in closed-access mode and 3% in open-access mode. The difference comes from the fact that, in open-access mode, the user can connect to neighbor FAPs if one of those FAPs becomes its best-server.

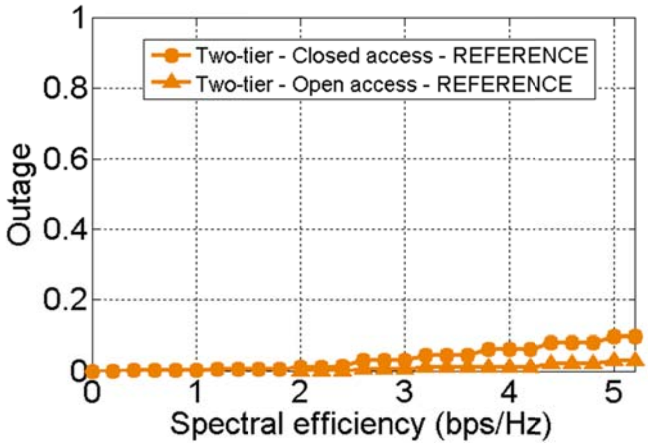


Figure 87. Scenario IA-5 - Spectral efficiency CDFs, as experienced by a FAP subscriber.

Figure 88 illustrates the impact of some FAP properties on the spectral efficiency predicted for FAP subscribers. The benefit is slightly lower when the FAP-to-FAP interference level increases (FAP density=50% or FAP activation ratio=100%). However, the spectral efficiency for 10dBm FAP transmit power is almost the same as for 20dBm.

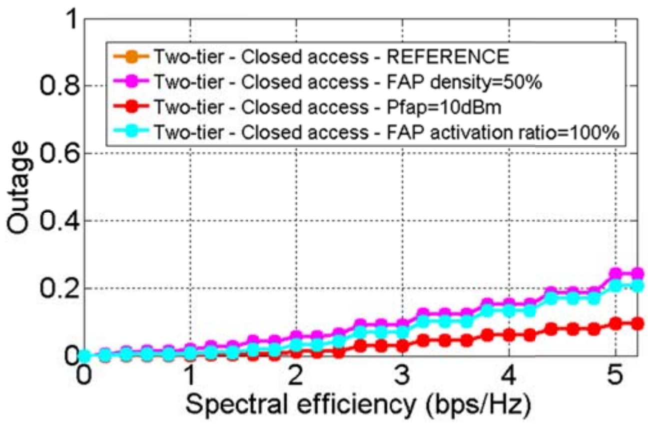


Figure 88. Scenario IA-5 - Impact of FAP properties on spectral efficiency, as experienced by a FAP subscriber.

Secondly, we focus on the impact for corporate FAP subscriber, who is located in the same floor as the FAPs. These results illustrate the performance that should be experienced in two different cases: (1) FAPs are in open-access mode; or (2) FAPs are in closed-access and the predicted user is a subscriber who belongs to the Closed Subscriber Group (CSG) of all FAPs.

Figure 89 gives the spectral efficiency CDFs at the whole FAP deployment floor. In the reference scenario, the average spectral efficiency is 3.6bps/Hz against 2.2bps/Hz in the same scenario with existing macro coverage (see Figure 64). It also shows the impact of some FAP properties:

- Increasing the FAP deployment density from 20% to 50% increases the spectral efficiency by 0.6bps/Hz on average.
- Reducing the FAP transmit power from 20dBm to 10dBm reduces the spectral efficiency by 1.8bps/Hz on average.
- Increasing the FAP activation ratio from 50% to 100% reduces the spectral efficiency by 1.2bps/Hz on average.

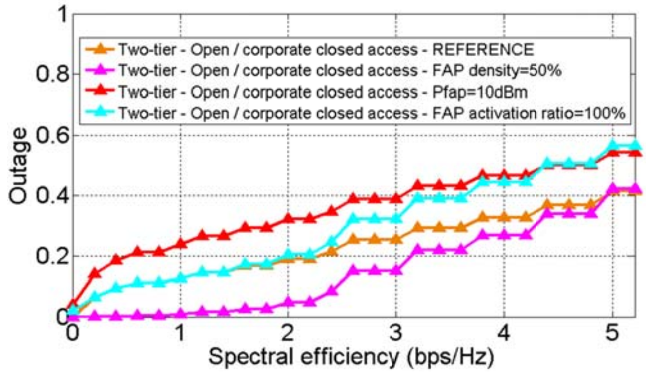


Figure 89. Scenario IA-5 – Impact of FAP properties on spectral efficiency, as experienced by a corporate FAP subscriber located in the FAP deployment buildings.

8.1.5.2 ***Scenario IA-6 – Spectral efficiency of a building FAP deployment***

Figure 90 compares the spectral efficiency CDFs in the two-tier network: the outage probability of the maximum spectral efficiency of the system (5.2bps/Hz) is 7% in closed-access mode and 4% in open-access mode.

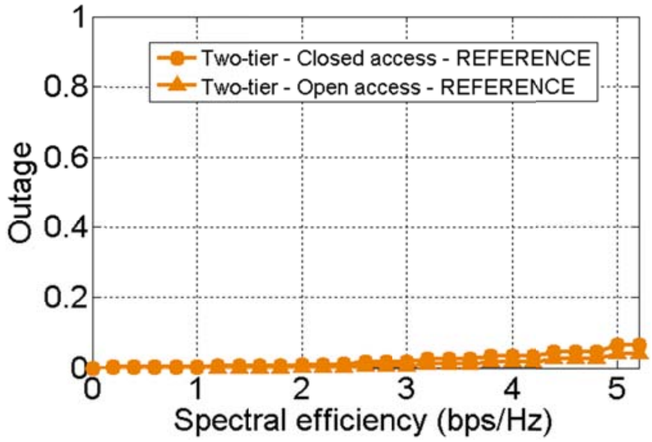


Figure 90. Scenario IA-6 - Spectral efficiency CDFs, as experienced by a FAP subscriber.

Figure 91 illustrates the impact of some FAP properties on the spectral efficiency predicted for FAP subscribers. The benefit is slightly lower when the FAP-to-FAP interference level increases (FAP density=50% or FAP activation ratio=100%). However, the spectral efficiency with 10dBm FAP transmit power is the same as with 20dBm.

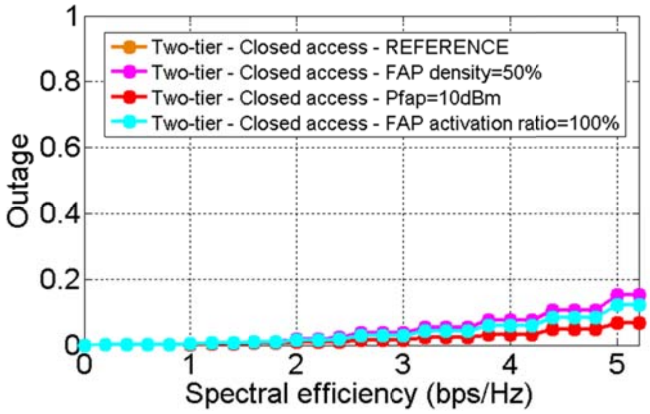


Figure 91. Scenario IA-6 – Impact of FAP properties on spectral efficiency, as experienced by a FAP subscriber.

Figure 92 illustrates the impact of FAP locations on the spectral efficiency predicted for FAP subscribers. The spectral efficiency distributions are barely the same inside FAP areas. FAP deployment in staggered rows provides a slightly better spectral efficiency since the FAP-to-FAP interference is lowered: the maximum spectral efficiency of the system (5.2bps/Hz) is reached with 1% outage probability against 5%-7% for other FAP locations.

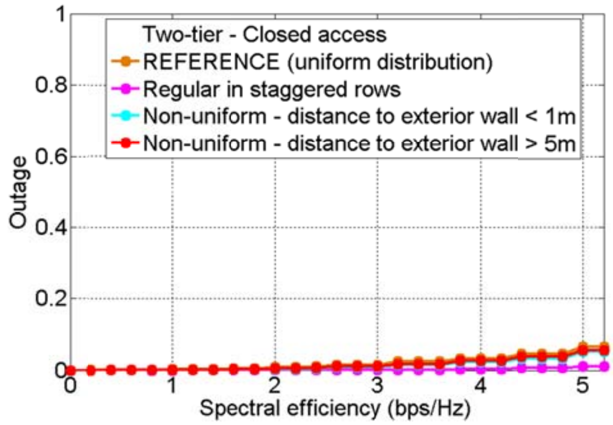


Figure 92. Scenario IA-6 - Impact of FAP locations on spectral efficiency, as experienced by a FAP subscriber.

Secondly, we focus on the impact for corporate FAP subscriber, who is located in the same floor as the FAPs. These results illustrate the performance that should be experienced in two different cases: (1) FAPs are in open-access mode; or (2) FAPs are in closed-access and the predicted user is a subscriber who belongs to the Closed Subscriber Group (CSG) of all FAPs.

Figure 93 gives the spectral efficiency CDFs at the whole FAP deployment floor. In the reference scenario, the average spectral efficiency is 4.8bps/Hz against 2.5bps/Hz in the same scenario with existing macro coverage; and the outage probability of the maximum spectral efficiency is 37% against 61% (see Figure 71). It also shows the impact of FAP properties:

- 20% FAP density is enough since 50% FAP density does not increase the spectral efficiency.
- Reducing the FAP transmit power from 20dBm to 10dBm does not reduce the spectral efficiency.

- Increasing the FAP activation ratio from 50% to 100% reduces the spectral efficiency by 1.8bps/Hz on average.

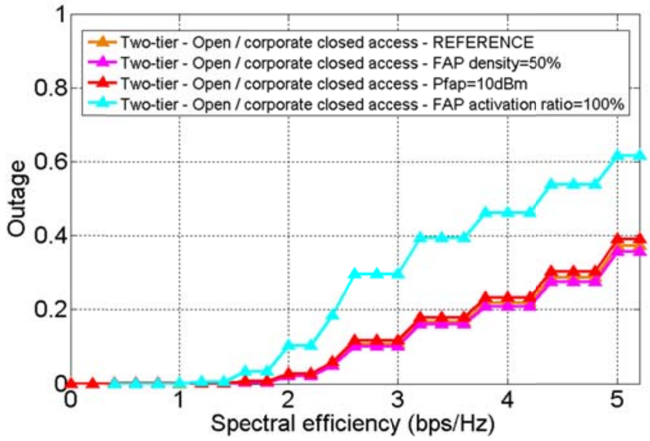


Figure 93. Scenario IA-6 – Impact of FAP properties on spectral efficiency, as experienced by a corporate FAP subscriber located in the FAP deployment buildings.

Figure 94 shows the impact of FAP locations on the spectral efficiency in the FAP deployment buildings, as experienced by a corporate FAP subscriber:

- Regular FAP deployment in staggered rows reduces the outage probability of the maximum spectral efficiency (5.2bps/Hz) from 37% to 27%.
- FAP deployment with a distance to the exterior wall lower than 1m increases the outage probability of the maximum spectral efficiency (5.2bps/Hz) to 43%.
- FAP deployment with a distance to the exterior wall greater than 5m offers the same spectral efficiency than a uniform distribution.

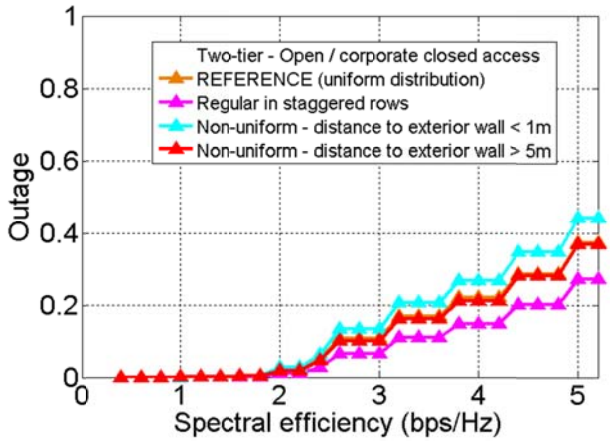


Figure 94. Scenario IA-6 – Impact of FAP locations on spectral efficiency, as experienced by a corporate FAP subscriber located in the FAP deployment buildings.

Figure 95 gives the spectral efficiency CDFs experienced by a corporate FAP subscriber located in the surrounding streets of the FAP deployment buildings. In the reference scenario, the average spectral efficiency is 3.7bps/Hz and the outage probability of the maximum spectral efficiency is 76%. It also shows the impact of FAP locations:

- Regular FAP deployment in staggered rows offers barely the same spectral efficiency (3.7bps/Hz on average).

- FAP deployment with a distance to the exterior wall lower than 1m increases the spectral efficiency to 4.2bps/Hz and reduces the outage probability of maximum spectral efficiency to 73%.
- FAP deployment with a distance to the exterior wall greater than 5m decreases the average spectral efficiency to 3.1bps/Hz and increases the outage probability of maximum spectral efficiency to 86%.

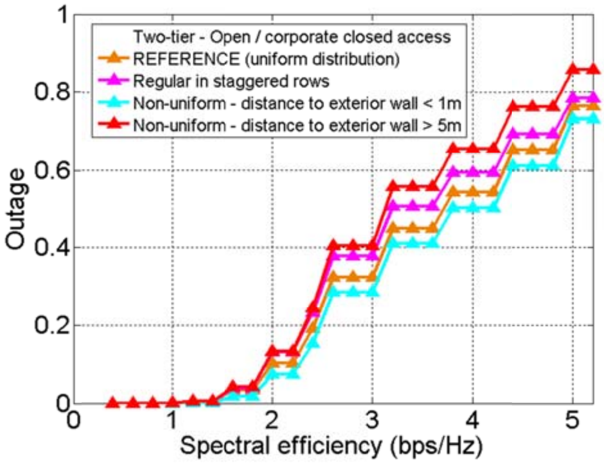


Figure 95. Scenario IA-6 – Impact of FAP locations on spectral efficiency, as experienced by a corporate FAP subscriber located in the surrounding streets of the FAP deployment buildings.

8.2 Cell performances for deployments with shared band allocation

8.2.1 **Equipartition of frequency band**

This Section summarizes the results obtained by means of the dynamic system simulator (described in 7.1, and complementing analysis performed in [Freedom-D51]) developed by DUN, based on the evaluation of interference variation with time for a series of transmission events, compliant with LTE frame structure, at the ms scale.

The algorithms have been run for a homogeneous deployment of 150 UEs, with increasing FAP penetration (10 to 60 indoor FAPs) addressing a coarse band partition (half/half) between the MBS and the femto network. The comparison is made over two sets of identical cell deployments and propagation losses among all transmitters. Moreover, this activity can be considered complementary to the evaluations made in [Freedom-D51].

The average nominal capacity per user, measured in Kbit/s/PRB, is reported in Figure 96. The left panel corresponds to the case of full band overlap, while on the right is reported the output for the partitioned band. In order to assess some considerations about the final capacity, it is necessary to consider also the results in Figure 97, representing the outage percentage per cell, i.e. the percentage of users unable to correctly perform a communication, as a result of the surrounding transmitters (including the MBS).

For a network implemented with a full band overlap, an increase of FAP penetration is characterized by a capacity increase of about 15%, while in the same conditions it is decreased of about 50% in the case of band partitioning. On the other hand, in the case of full overlap, the interference component provides the worst transmission conditions: indoor MUEs strongly suffer from FAP interference (completely unable to communicate in the case of full overlap). The overall outage decreases of about 20% (i.e. better network conditions at system level) when increasing the number of FAPs, while on the other hand outage increases of about 12% with the number of FAPs in the case of band partitioned.

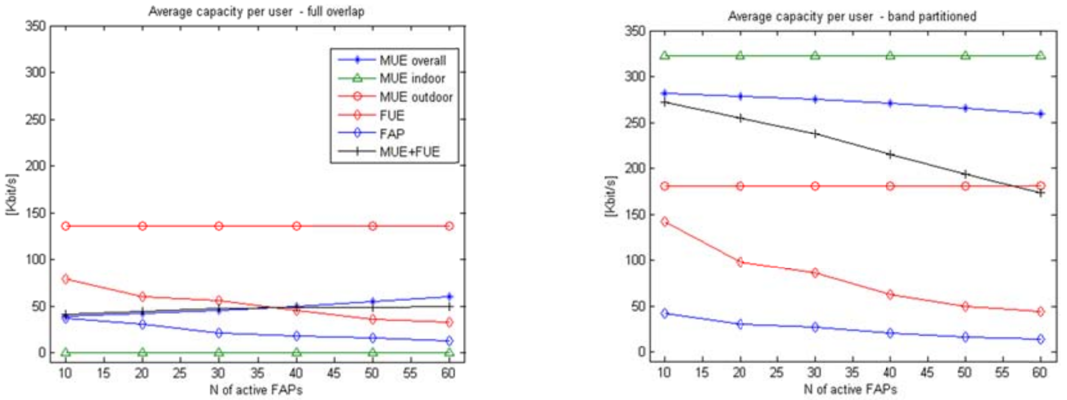


Figure 96. Average capacity per user per PRB. Left: full overlap band; right band equally partitioned.

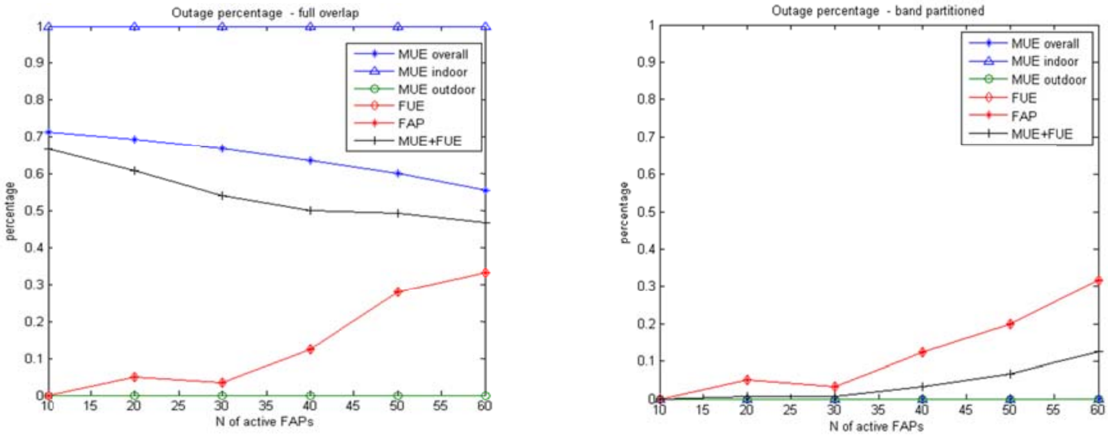


Figure 97. Outage percentage per cell. Left: full overlap band; right band equally partitioned.

From the above considerations, one can conclude that although at a first sight the band partition between macro network and femto network can significantly damp interference, in the perspective of a massive FAP deployment the overall system gains major benefits when the band is fully overlapped. Of course, the test is based on a very simple partition method and leaves room to more sophisticated techniques which, anyway, have to tackle a strongly increasing number of interferers, thus leaving room to implementation issues, which are not within the scope of the analysis of this activity.
The results are summarized in Table 14.

Effect of increasing NW FAP penetration		Full overlap	Band equipartition
Overall Capacity	MUE	+50%	-8%
	MUE indoor	0	0
	MUE outdoor	0	0
	FUE	-60%	-66%
	UE=MUE+FUE	+19%	-35%
Outage	MUE	-16%	0
	MUE indoor	0	0
	MUE outdoor	0	0
	FUE	30%	+31%
	UE=MUE+FUE	-20%	+13%

Table 14. System performances variation when increasing FAP penetration. Comparison between full band overlap and band equipartition. Note that outage changes with FAP penetration.

8.2.2 Variable band partition

In this Section we present the results of system simulations, complementary to those presented in Section 6 of document [Freedom-D51]. The band partition between the MBS and the femto layer can be designed as a rigid sharing or as a dynamic sharing. Indeed, traffic analysis shows that for 3 applications running on a mobile terminal, the used PRBs by a FUE have an occupancy level of order of 5-10%.

The system simulator has been run for a set of scenarios considered of interest for the deployment characteristics:

- Scenario 1: Homogeneous dense, (785 UEs, 254 FAPs);
- Scenario 2: Inhomogeneous sparse, 4 buildings, 150 UEs, 60 FUEs;
- Scenario 3: Inhomogeneous dense, 20 buildings, 300 UEs, 120 FAPs.

The outcomes in terms of average throughput per PRB and outage are reported in the following sub-section.

We present results in the case the femto network transmits over the whole band and the MBS occupancy increases from 10% to 100% overlap and in the opposite case in which the MBS transmits over the whole band and the femto tier occupies an increasing number of PRBs, providing a comparison of results.

8.2.2.1 *MBS increasing band occupancy*

The simulation results presented in this Section summarize the system performances considering a femto tier with potential occupancy of the whole band and while the transmission of the MBS (and of MUEs) occupy an increasing number of bands, from 10 to 100% of overlap.

The average throughput per user per PRB for the three scenarios is reported in Figure 98, Figure 99 and Figure 100, respectively.

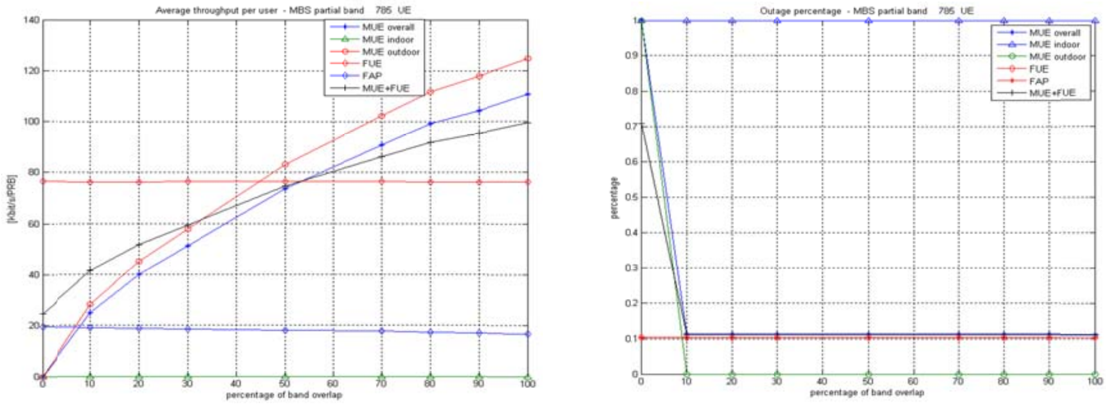


Figure 98. Variation of performance metrics for homogeneous scenario (785 UEs, 254 FAPs). Increasing band occupancy by MBS tier. Left: capacity per PRB; right, outage.

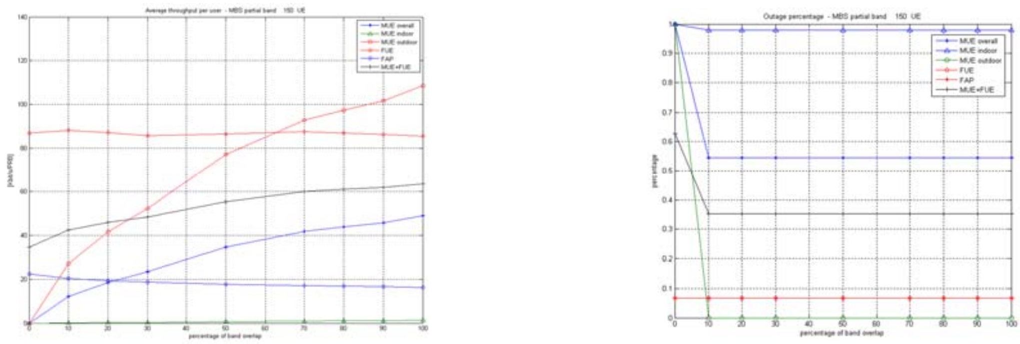


Figure 99. Variation of performance metrics for inhomogeneous scenario with 4 buildings. Increasing band occupancy by MBS tier. Left: capacity per PRB; right, outage.

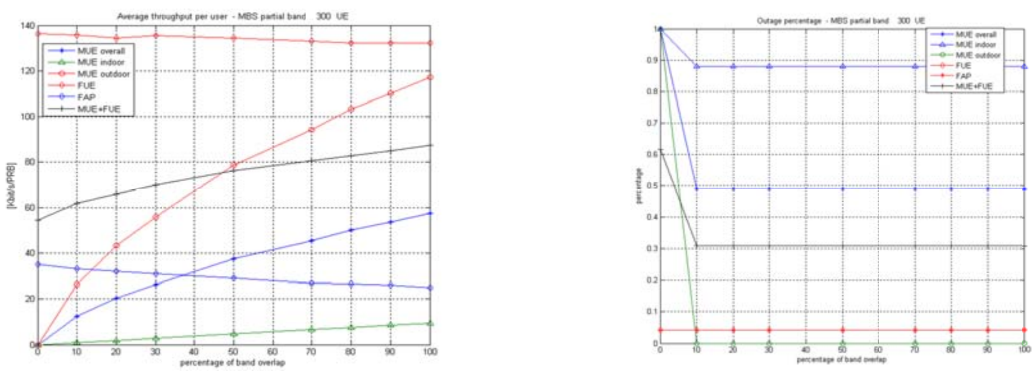


Figure 100. Variation of performance metrics for inhomogeneous scenario with 20 buildings. Increasing band occupancy by MBS tier. Left: capacity per PRB; right, outage.

The plots show how the same conclusions can be driven for all cases considered. Increase of band usage by the MBS implies an increase of throughput per user for the macro network, with a reduction of outage for indoor users which are those most suffering for interference from the FAPs. Behavior of the femto network, whose band is fixed, is poorly affected by a band overlap increase.

8.2.2.2 *FEMTO tier increasing band occupancy*

For the case in which the MBS uses the whole band and the femto network occupies an increasing part of overlapping band, Figure 101 reports the relevant scenario of 5 FAP areas, including 20 buildings deployed in the cell. The throughput of the FAPs increases linearly with the band increase, while throughput of indoor MUEs decreases steadily, as effect of increasing indoor interference, confirmed by a growth also of outage of indoor MUEs.

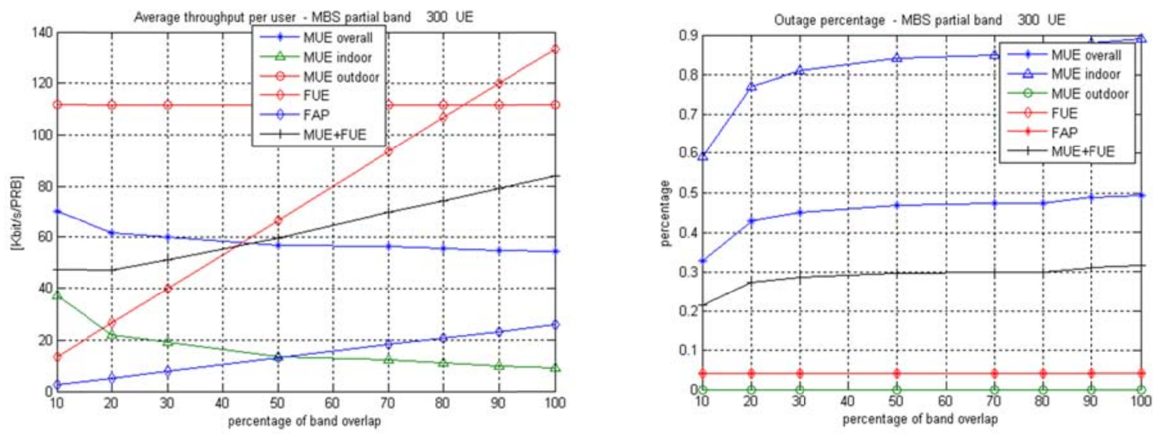


Figure 101. Variation of performance metrics for inhomogeneous scenario with 20 buildings. Increasing band occupancy by femto tier. Left: capacity per PRB; right, outage.

8.3 System performances for deployments with mobility

The dynamic system simulator has been implemented to evaluate system performances also in the case of a scenario whose characteristics vary with time, either because transmitters move in their environment, or because persons and objects in the surrounding move around, leading to short term variations of the relative pathlosses, thus implying variations on interference relations. To this purpose, SIR has produced some deployments of users in a real urban environment which have been used as input for the system simulator and processed to get system metrics.

8.3.1 **Mapped scenario**

Very realistic deployment scenarios are simulated in Paris dense urban, using a high-resolution 3D vector map and site-specific propagation models (ray-tracing in particular). The macro layout is composed of one base-station with an omni-directional antenna located above a rooftop (42m above the ground). The FAPs are randomly distributed in the different corporate building floors, after part of the building blocks (20% actually) have been randomly determined as corporate. Table 15 gives the simulation parameters for each realized scenario. Scenarios N1 and N2 have similar number of FAPs, FUEs and MUEs, however they result from two different random deployment runs. Same comment applies on scenarios N3 and N4. As well on scenarios N5 and N6.

Channel traces are obtained from the process described in section 7.1.2. Two different methods have been used to generate channel (and path-loss) variations over the 1-second simulation duration:

1. Considering the user is moving with velocity 3km/h in a random direction;
2. Considering the user is static, but random surrounding human activity can produce time-varying path obstructions

Scenario Id	N1	N1_a	N2	N3	N4	N5	N6
# FAPs	98	98	98	154	151	199	201
#FUEs	98	98	98	154	151	199	201
# outdoor MUEs	8	8	7	7	10	13	13
# indoor MUEs	47	47	46	50	52	40	42
FUE mobility	moving	50% moving / 50% static	moving	moving	moving	moving	moving
MBS tx power	46dBm						
MBS antenna gain	10dBi						
FAP tx power	20dBm						
FAP antenna gain	5dBi						
Central frequency	2GHz						
Signal bandwidth	10MHz						

Table 15: Simulation parameters for mapped scenarios.

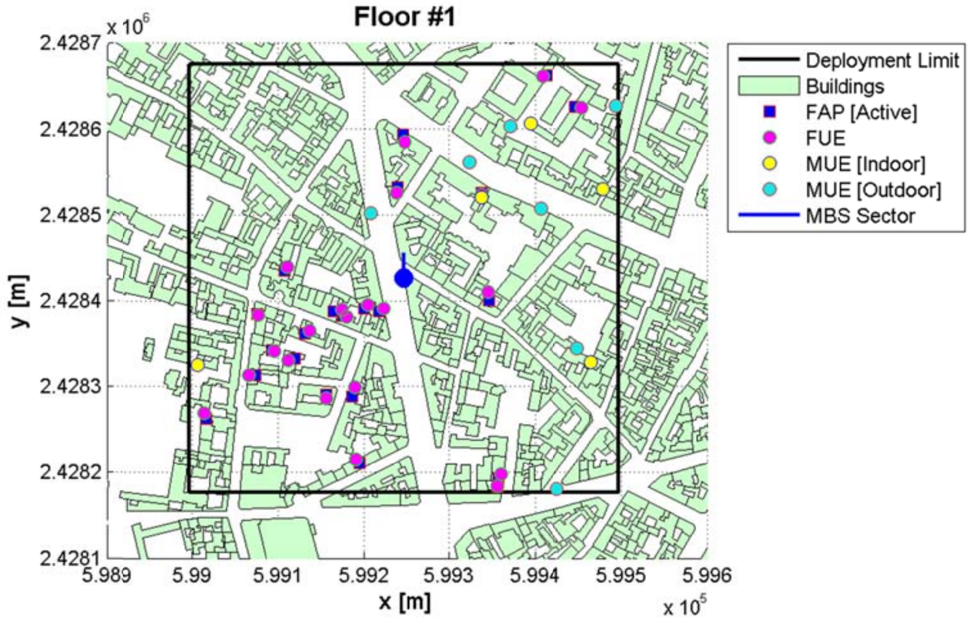


Figure 102: FAP and user distribution in the street and building ground-floor in scenario N3.

Only scenario “N1_a” is making use of this second approach, where

- Half the indoor users are considered static;
- Half the static users have no surrounding human activity;
- Consequently, 50% indoor users undergo channel variations similar to scenario “N1”; 25% indoor users undergo channel variations resulting from surrounding human activity; 25% indoor users do not undergo any channel variation.

Figure 103 gives the statistical distribution of the channel gain standard deviation over 1 second, and thus characterizes channel variations for both static and moving users. Median value is much higher for moving users (1.4dB against 0.1dB), however the channel behavior is very different from one static user to another; a standard deviation greater than 6dB is observed for 5% static users.

Figure 104 gives another illustration of the human activity impact, time variations are observed for (a) the user considered as moving and (b) the same user considered as static with an obstruction occurring on a dominant path.

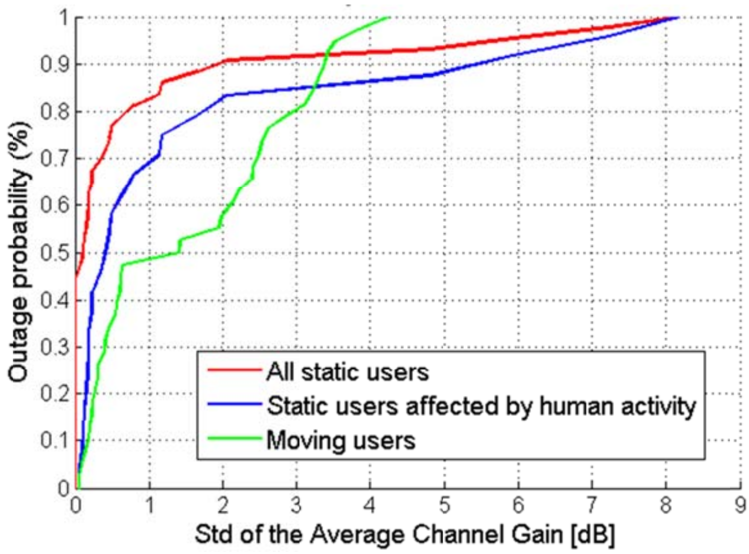
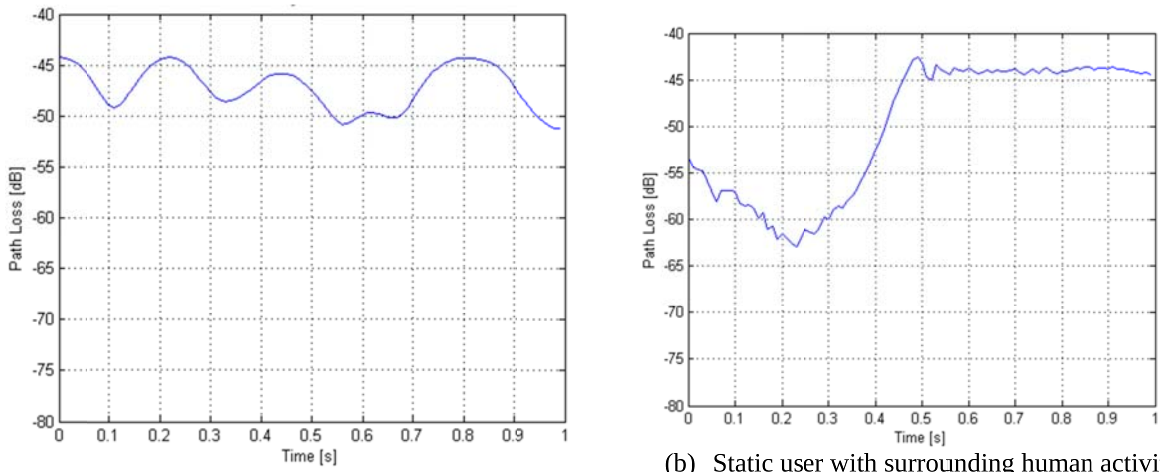


Figure 103: Standard deviation of the average channel gain over the 1s simulation duration, for different user categories simulated in scenario "N1_a".



(a) Moving user.

(b) Static user with surrounding human activity.

Figure 104: Time-varying path-loss for a FAP-FUE link where FUE is (a) considered as moving in scenario "N1" and (b) considered as static with surrounding human activity in scenario "N1_a".

8.3.2 System behavior

The summary of results produced by running the system simulator with a realistic, time-varying scenario is reported in Table 16, including characteristics of the different deployments.

deployment	'SIR_N1'	'SIR_N1_a'	'SIR_N2'	'SIR_N3'	'SIR_N4'
FUEs	98	98	98	154	151
UEs	153	153	151	211	213
FAP_on_balcony	0	0	0	0	0
MUE_indoor	47	47	46	50	52
MUE_outdoor	8	8	7	7	10
capaMUEs_overall	95.3	97.0	69.8	65.7	77.5
capaMUEs_out	192.5	187.7	182.6	98.7	185.6
capaMUEs_in	78.7	81.6	52.7	61.0	56.6
outageMUE	0.42	0.42	0.42	0.39	0.48
outageMUEin	0.49	0.49	0.46	0.42	0.58
outageMUEout	0	0	0.1429	0.1429	0
capaFUEs	254.2	233.3	255.7	219.7	187.3
outageFUE	0.18	0.17	0.13	0.16	0.19
capaFAPs	61.3	57.5	62.9	54.4	45.1
outageFAP	0.18	0.17	0.13	0.1558	0.19
outageUE	0.27	0.26	0.23	0.2180	0.28
capa_overallUE	167.2	158.4	168.4	153.1	128.9
UE	153	153	151	211	213
FAP	98	98	98	154	151

Table 16. System performances for different realizations of a mapped scenario, based on SIR realizations. The meaning of the adopted variables is explained in the following Table 17.

FUEs	Number of FUEs
UEs	Number of overall UEs
FAP_on_balcony	Number of FAPs on balcony
MUE_indoor	Number of MUEs indoor
MUE_outdoor	Number of MUEs outdoor
capaMUEs_overall	Capacity of all MUEs, in Kbit/s/PRB
capaMUEs_out	Capacity of MUEs outdoor only, in Kbit/s/PRB
capaMUEs_in	Capacity of MUEs indoor only, in Kbit/s/PRB
outageMUE	Outage of all MUEs (ratio, percentage/100)
outageMUEin	Outage of MUEs indoor only (ratio, percentage/100)
outageMUEout	Outage of MUEs outdoor only (ratio, percentage/100)
capaFUEs	Capacity of FUEs, in Kbit/s/PRB
outageFUE	Outage of FUEs (ratio, percentage/100)
capaFAPs	Capacity of FAPs, in Kbit/s/PRB
outageFAP	Outage of FAPs (ratio, percentage/100)
outageUE	Outage of overall UEs (ratio, percentage/100)
capa_overallUE	Capacity of overall MUEs, in Kbit/s/PRB
UE	Number of UEs (MUEs and FUEs)
FAP	Number of FAPs

Table 17. Meaning of system variables.

The plots in Figure 105, Figure 106 and Figure 107 report the temporal variation of MUEs, FAPs and FUEs SINR and capacity for SIR scenario N1, with a summary of average throughput per user in Figure 108. The same can be said for Figure 109, Figure 110 and Figure 111 for the SIR scenario N1a. The change in the environment and thus on all pathloss relations among transmitters reflects in the

SINR temporal variation. The following figures address the impact on average throughput per PRB that can be gained by users.

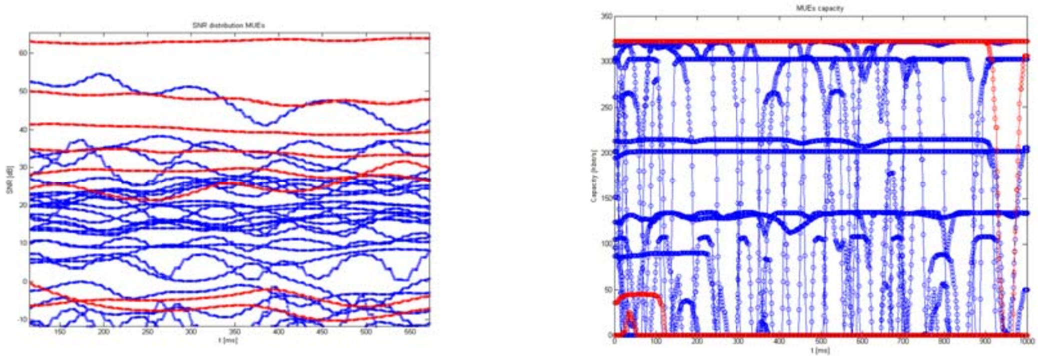


Figure 105. Variation of MUEs performance metrics for mapped N1 scenario. Left: capacity per PRB; right, outage. Red, indoor; blues, outdoor.

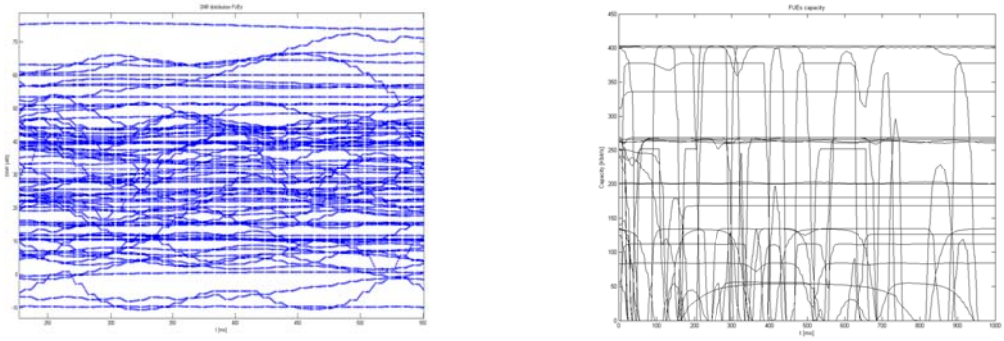


Figure 106. Variation of FUEs performance metrics for mapped N1 scenario. Left: capacity per PRB; right, outage.

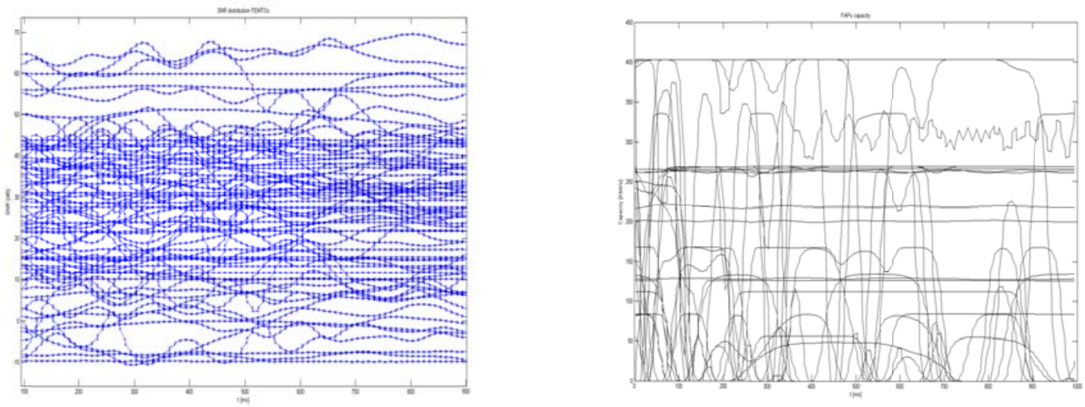


Figure 107. Variation of FAPs performance metrics for mapped N1 scenario. Left: capacity per PRB; right, outage.

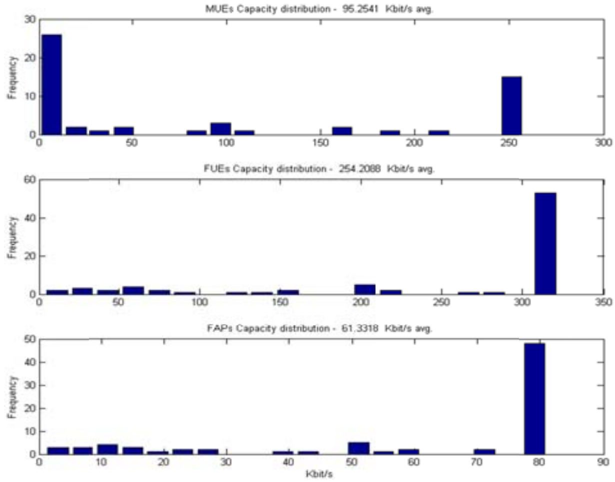


Figure 108. Distribution of average throughput per user for mapped N1 scenario.

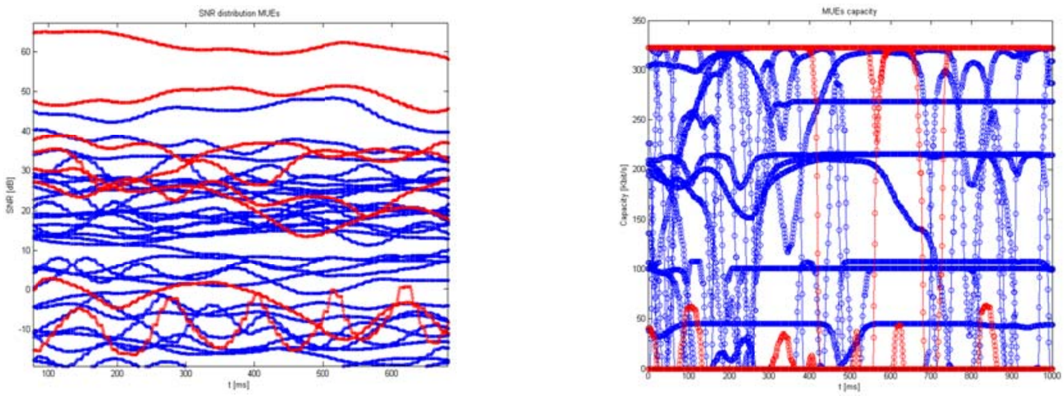


Figure 109. Variation of MUEs performance metrics for mapped N1a scenario. Left: capacity per PRB; right, outage. Red, indoor; blues, outdoor.

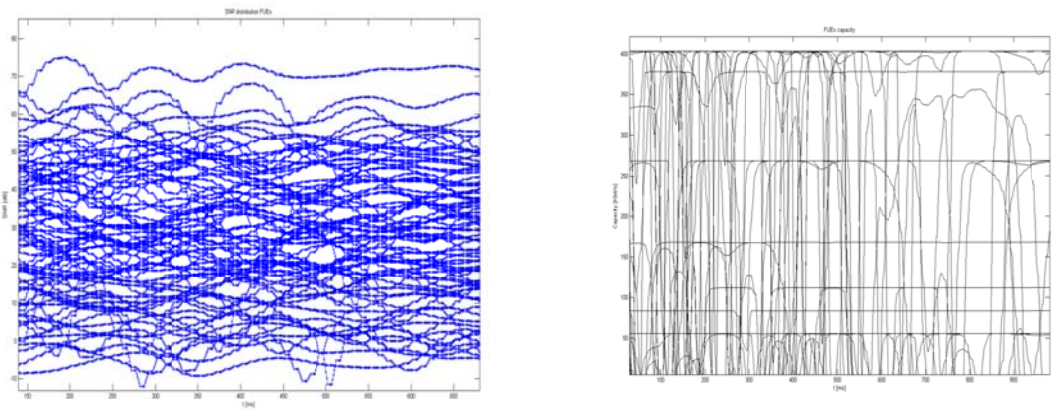


Figure 110. Variation of FUEs performance metrics for mapped N1a scenario. Left: capacity per PRB; right, outage.

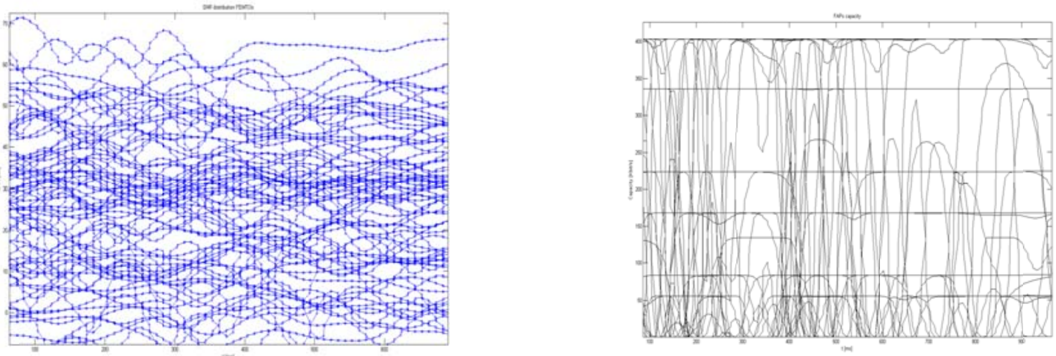


Figure 111. Variation of FAPs performance metrics for mapped N1a scenario. Left: capacity per PRB; right, outage.

8.3.3 System metrics

A comparison of system performance for the SIR scenarios evaluated is summarized in Figure 112 and Figure 113 expressed by average throughput per user per PRB and outage, for all different types of transmitters. Apart from slight variations in absolute terms, all scenarios show similar values for the metrics associated to MUEs and FUEs. For SIR scenarios N1, N1a and N4, all outdoor MUEs show zero outage.

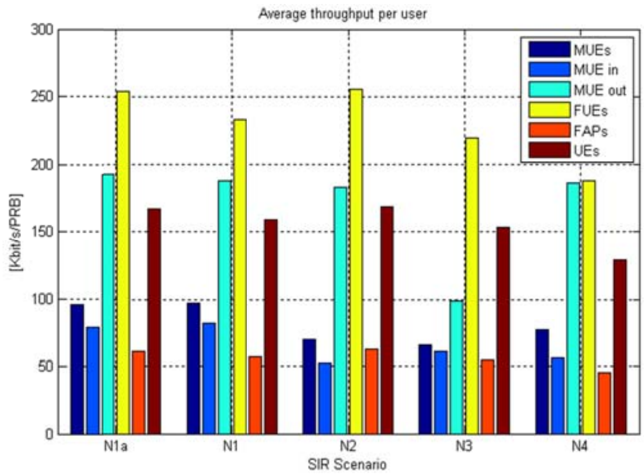


Figure 112. Variation of average throughput per user for mapped scenario.

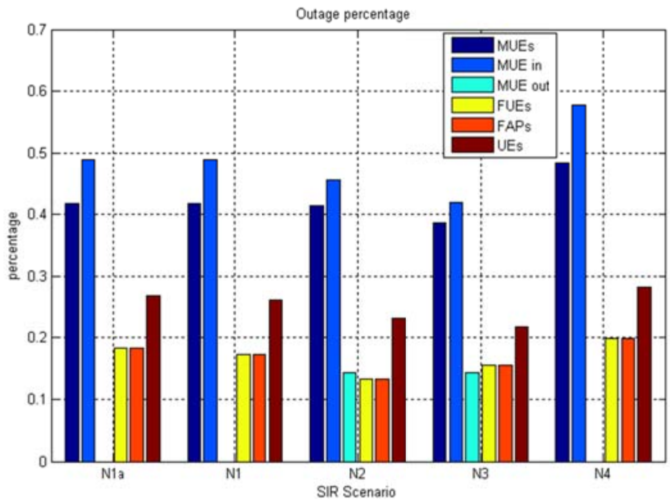


Figure 113. Variation of outage for mapped scenario.

8.4 *System performances for deployments with GO*

This Section reports the system performances when a GO is implemented for the DL of the FAPs, realized in three scenarios of interest:

- Homogeneous
- Inhomogeneous
- Mapped, as SIR N1 without time variation.

The metrics for three study cases are reported in Figure 114, Figure 115 and Figure 117, respectively, while Figure 116 shows the GO output for one of them.

8.4.1 **Homogeneous scenario**

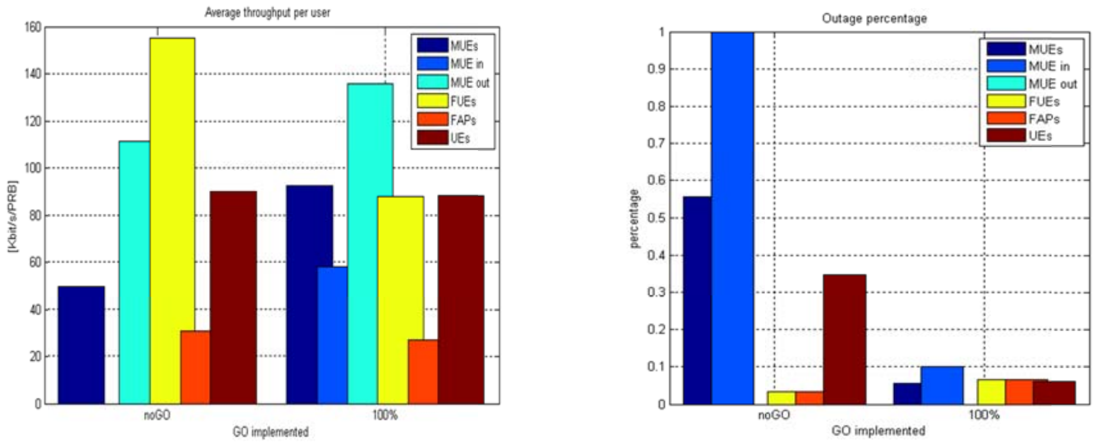


Figure 114. Comparison of overall system performances with or without implementation of GO for FAPs DL. Left, average throughput per PRB; right, outage. Evaluation performed in a homogeneous scenario with 150 UEs and 60 FAPs.

8.4.2 **Inhomogeneous scenario**

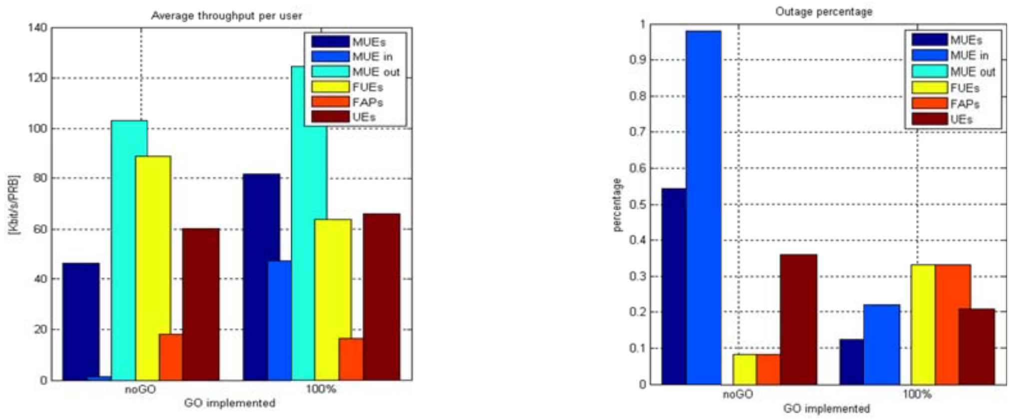


Figure 115. Comparison of overall system performances with or without implementation of GO for FAPs DL. Left, average throughput per PRB; right, outage. Evaluation performed in an inhomogeneous scenario with 150 UEs and 60 FAPs.

8.4.3 Mapped scenario – SIR N1

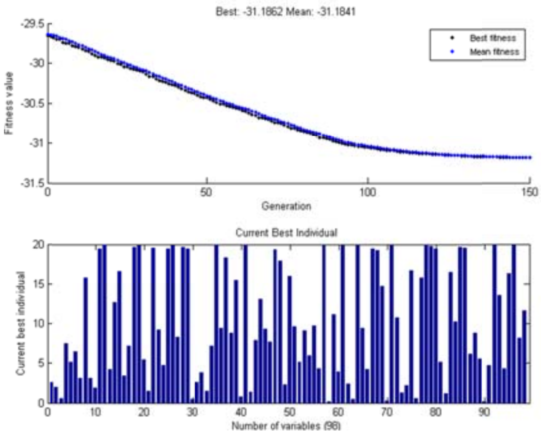


Figure 116. GO algorithm optimization for SIR scenario N1.

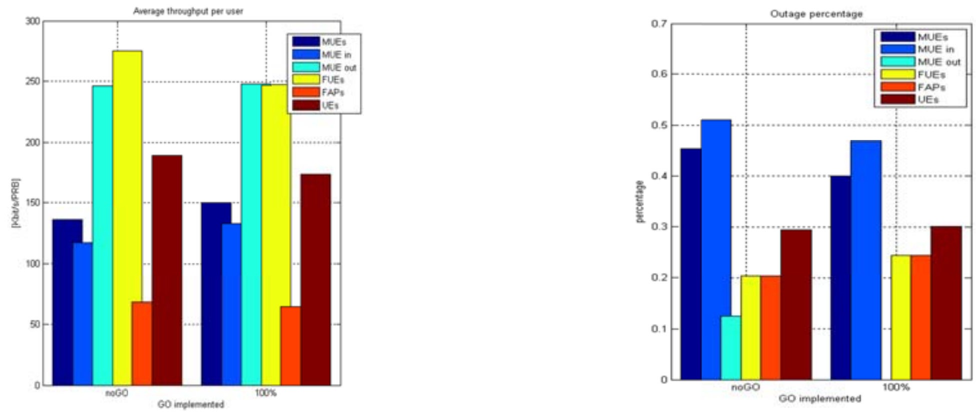


Figure 117. Comparison of overall system performances with or without implementation of GO for FAPs DL. Left, average throughput per PRB; right, outage. Evaluation performed in a static scenario, mapped SIR N1.

8.4.4 Conclusions about GO implementation at system level

The three study cases, whose metrics are reported in Figure 114, Figure 115 and Figure 117 show that the overall system performances benefit from the optimization process, both in terms of average throughput and of outage, especially when focusing on MUEs. Indeed, the optimization algorithm assigns different values of transmission power to different units, which are typically lower than the maximum power set for the un-optimized case. The transmission power of FAPs (as shown for example in Figure 116) is indeed reduced to minimize their reciprocal interference, while power of transmission of other interferers (mainly indoor MUEs) is still at maximum value. The overall effect is that nominal throughput per PRB of FAPs is reduced, while that of MUEs improves. On the other hand, values of metrics refer to throughput per PRB. If all MUEs in the macro network compete for resources assignment, sharing at most 100 PRBs (or less, depending on the LTE bandwidth), for the femto network the situation is far more sustainable. In fact, one FAP can serve up to 4 FUEs only, and then the apparent decrease of throughput per user per PRB is not going to impact significantly the data traffic flow. Thus, a reduction of transmission power according to the GO criterion guarantees comparably the same QoS to FUEs while significantly improving performances of other users (FUEs and MUEs in the surroundings).

A difference between the tested scenarios is that the design of synthetic ones (i.e., homogeneous and inhomogeneous) is characterized by a deep penetration of indoor MUEs which are much closer to FAPs, while in the mapped developed by SIR indoor MUEs are more sparse.

Analyzing the right panels of the Figure 114, Figure 115, emerges that in the synthetic in more dense deployments scenarios outage is reduced of up to 80%, while from Figure 117 referring to SIR scenario outage is improved of about 10%, as it is sparser.

8.5 MBS offload and QoS

In this Section we report the system performances evaluation in a scenario deployment where traffic is produced by UEs running specific applications. For this test, the inhomogeneous scenario (150 UEs, 60 FUEs, 4 buildings) has been chosen as a reference case.
The system simulator takes into account:

- Deployment
- SINR of UEs
- Packet data flow.

In order to quantify the impact on QoS of each unit (both MUEs and FUEs) when deploying FAPs, this activity has been designed by comparing the system performances of a macro network when offloading traffic by attaching some (indoor) MUEs to (indoor) FAPs. The simulations take into account different traffic flows:

- in a macro network with 120 MUEs
- in the same macro network with 90 MUEs
- data transmitted when the 30 MUEs are FUEs attached to nearby FAPs.

The comparison is carried out by considering the different levels of SINR for indoor UEs when attached to the MBS or to a FAP, its impact on PDU-ER and thus on QoS. Finally, we provide an estimate on the extra energy consumption as a consequence of NACK packets that need retransmissions, evaluated in both cases of UE attached to the MBS or to a FAP.

8.5.1 **MBS traffic flow for 120 MUEs**

In this Section is reported the dynamic simulator output of traffic flow through the MBS. 120 MUEs are equally divided in three types, depending on the number and type of applications running on mobile devices:

- VoIP
- VoIP and homogeneous stream (FTP-like)
- VoIP, FTP, and bursty (HTTP-like).

Figure 118 shows a snapshot at certain instant of time users’ queues, while the right panel reports the instantaneous PDU-ER of the first four MUEs.

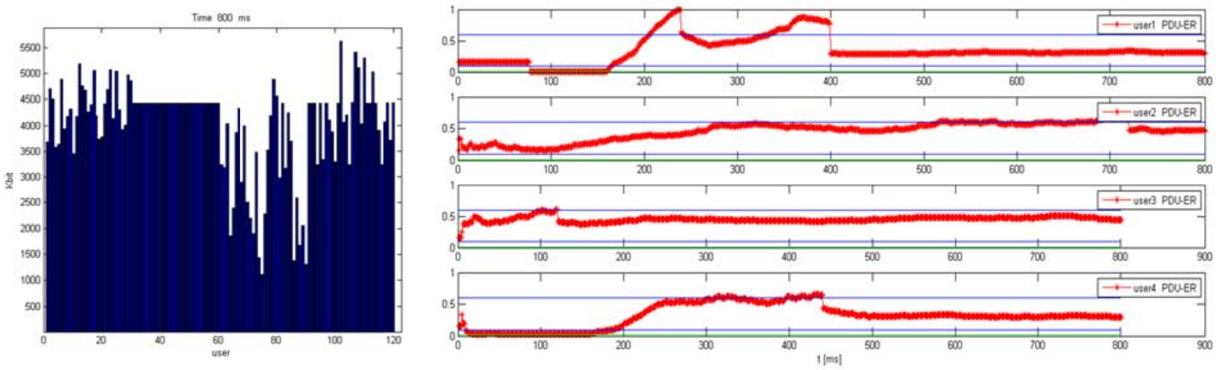


Figure 118. Traffic processing snapshot. Left: queue per user. Right: visualization of PDU-ER vs time for 4 users.

The left panel of Figure 119 reports the plot of SINR vs time, while the right panel the MCS variations, for the first 4 users. MCS is changed when SINR values are near the threshold for MCS assignments (see, for reference, Table 5 of [Freedom-D51]) or when the packet flux is too high to be efficiently served keeping the current MCS.

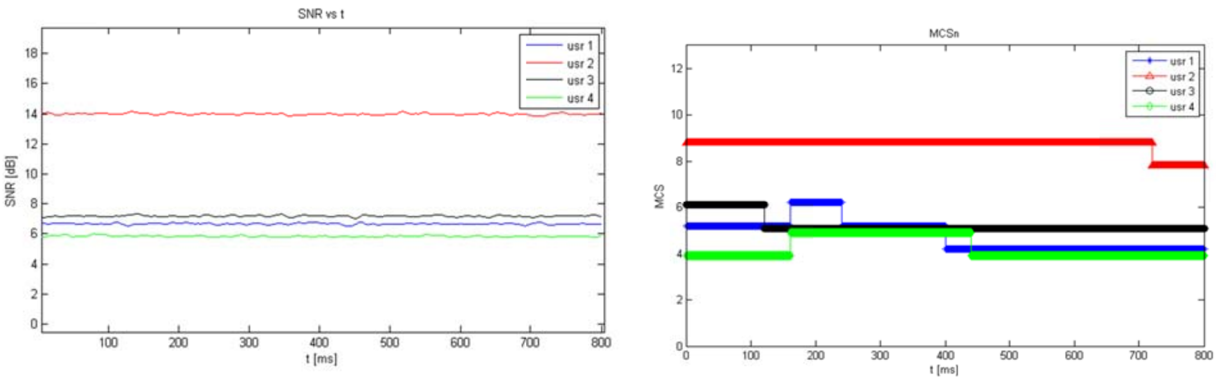


Figure 119. Traffic processing snapshot for 4 users. Left, SINR vs time; Right, MCS variation vs time depending on PDU-ER.

Figure 120 shows the temporal flow of packets allocated by the MBS RRM adopting the schedler described in Section 7.1.4.2, while Figure 121 shows a detail of one of the packet fluxes. The three lines must be interpreted as follows:

- **Noerr**. Net information data output as from the application, which would be case of perfect link connection (PDU-ER=0), every packet sent is received and there are no retransmissions;
- **Effective**. Data output including retransmissions due to NACK of packets. It is typically higher than Noerr.
- **Gross**. Once a user has been assigned by the RRM a certain PRB with the corresponding MCS, on air it is transmitted the whole PRB, although the net information encoded can be much less that the available number of bits.

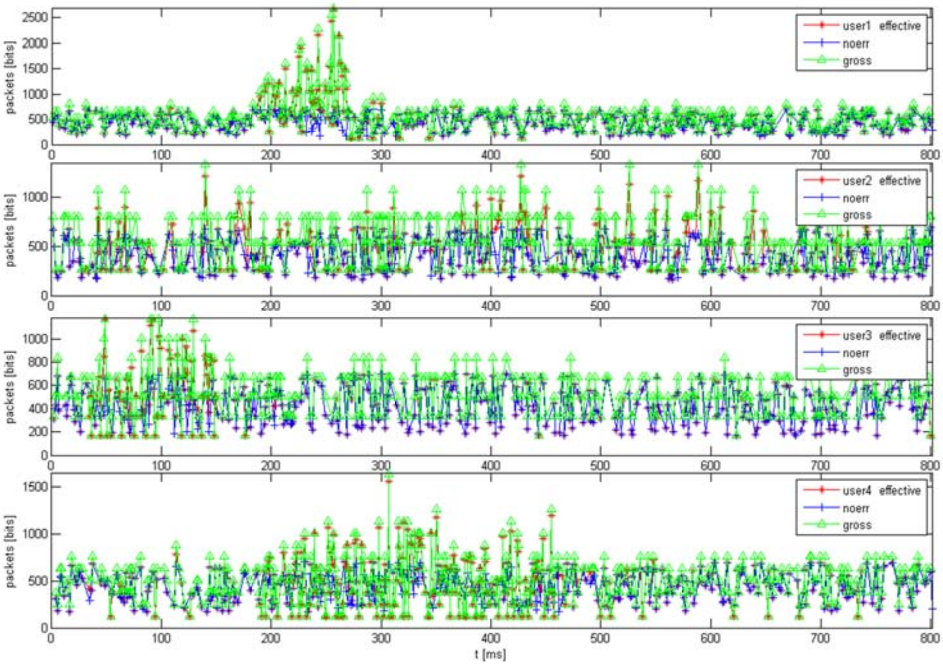


Figure 120. Traffic processing output, shown for 4 MUEs. Effect of PDU-ER and packets rescheduling on data flow.

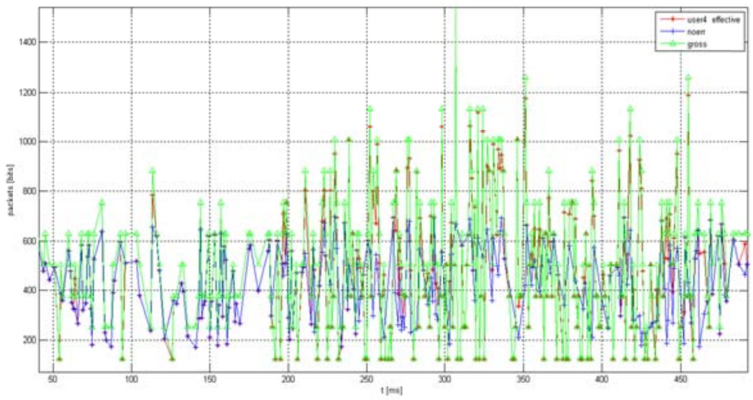


Figure 121. Traffic processing output, detail of traffic for one MUE. Comparison of application traffic and effective traffic including PDU-ER and fixed packet dimensions.

Some of the results of the processed traffic outputs are shown in Figure 122. The left panel reports the distribution of extra power consumption between traffic considered for perfect link conditions, i.e. without repetitions of packets, and effective traffic necessary to correctly receive information data. NACK packets transmitted at time T_1 are indeed rescheduled at a later time T_2. If the application requirements already scheduled a packet at T_2, then no extra transmissions are necessary, otherwise a new transmission event is added to the user queue. Also in the first case, once the bits queued are summed with the repeated ones, they need again to be fragmented in packets with the size allowed by the MCS and eventually a portion of this could again receive a NACK and be (partly) queued at a later time.

The right panel summarizes the distribution of packet loss for MUEs, measured as the number of packets with NACK and needing re-sending, thus lengthening the user's queue.

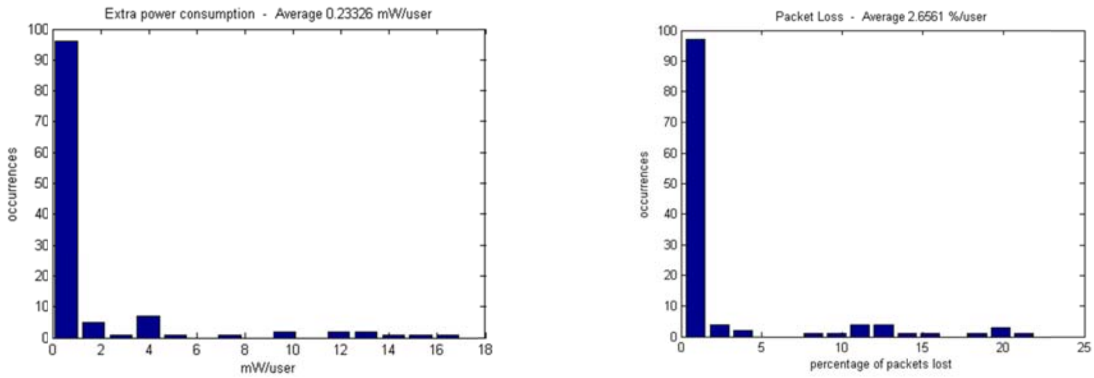


Figure 122. Traffic processing output. Left, distribution of extra power consumption due to packets rescheduling. Right, distribution of percentage of packets rescheduled.

Figure 123 shows for each MUE the relation between SINR and packet loss (in percentage of rescheduled packets), and extra power expenditure due to retransmissions. Users from 51 to 80 are those indoor users that will be attached to a FAP when offloading the MBS. Thus, the benefit of attaching some users to FAPs ensures to provide better links to users in worse transmission conditions, gaining better overall performances to the whole system.

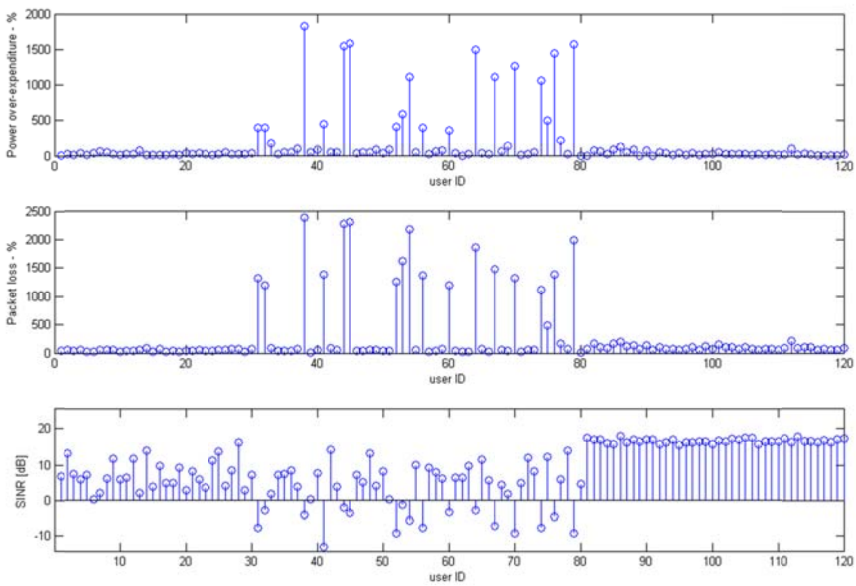


Figure 123. Traffic processing output per user, effect of PDU-ER and packets rescheduling. Top, power over-expenditure; middle, packet loss; bottom, average SINR.

Figure 124 summarizes the load on the MBS due to the traffic of 120 MUEs. The meaning of the three colours is the same as above when detailed for a single user. Note how effective traffic increases in the first part of transmissions when MCS is adapted to ensure QoS such as to process queues.

Figure 125 shows for each user the difference between information data and packets sent over the air.

8.5.2 MBS traffic flow for 90 MUEs

This Section reports the same metrics discussed for the case of 120 MUEs when 30 of them have been attached to a FAP. The traffic of the remaining 90 MUEs and its flow through the MBS shows similar features but the load on the MBS is indeed reduced, while disadvantaged MUEs indoor are now in better transmission conditions, as summarized in next Section.

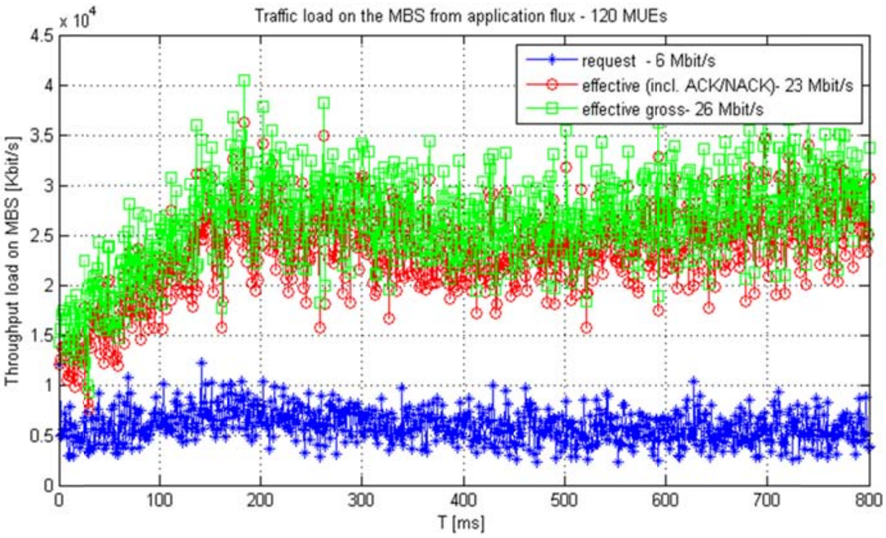


Figure 124. MBS Traffic flow, 120 MUEs.

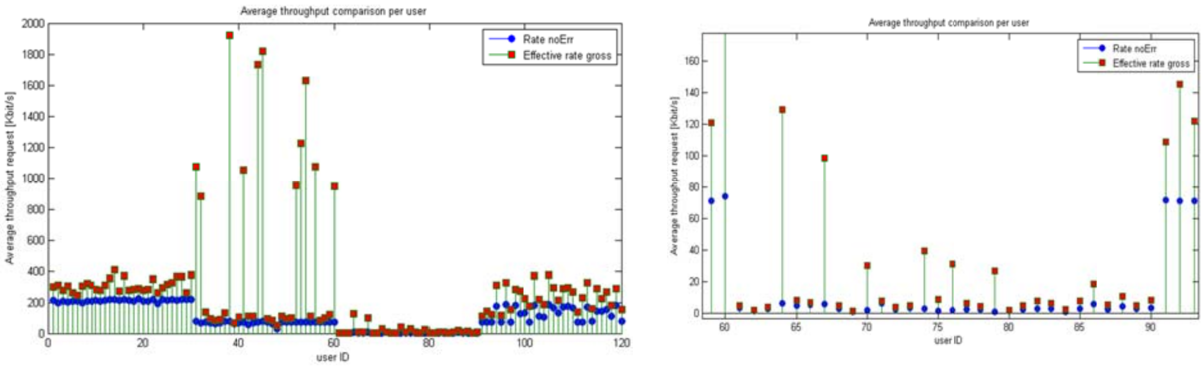


Figure 125. Traffic processing output. Left, comparison of traffic load per user. Right, zoom over the set of outdoor MUEs.

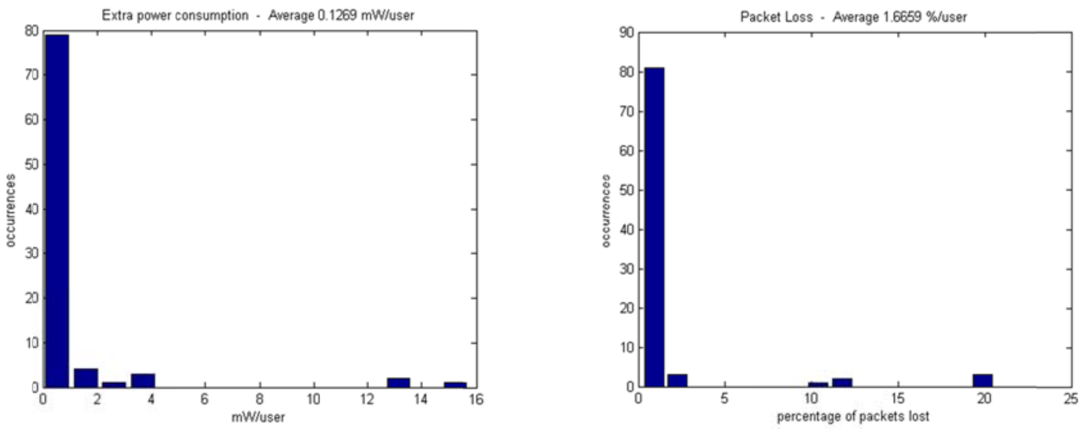


Figure 126. Traffic processing output. Left, distribution of extra power consumption due to packets rescheduling. Right, distribution of percentage of packets rescheduled.

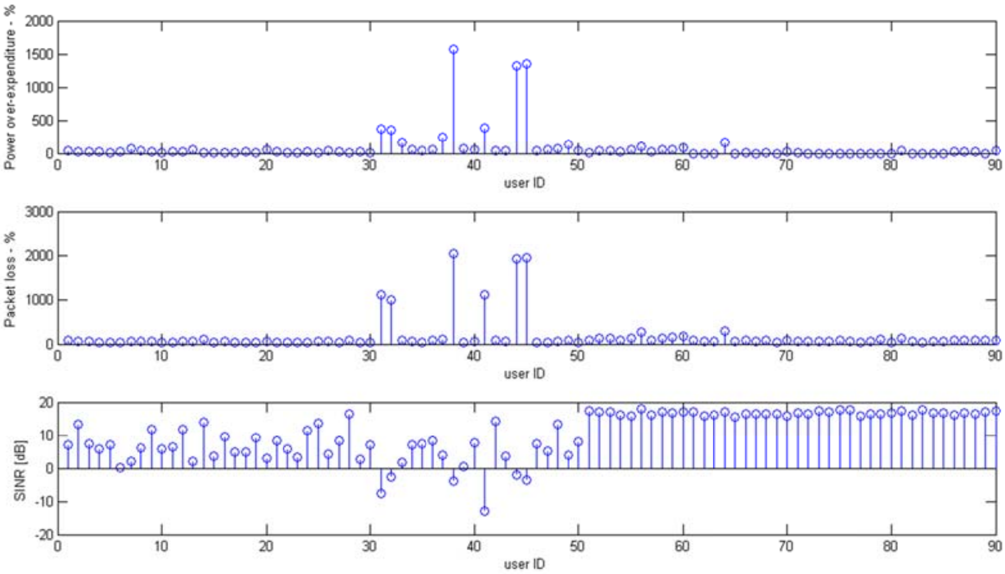


Figure 127. Traffic processing output per user, effect of PDU-ER and packets rescheduling. Top, power over-expenditure; middle, packet loss; bottom, average SINR.

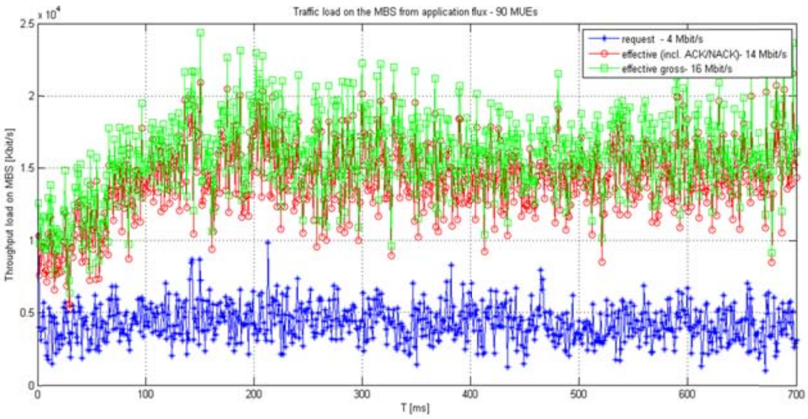


Figure 128. MBS Traffic flow, 90 MUEs.

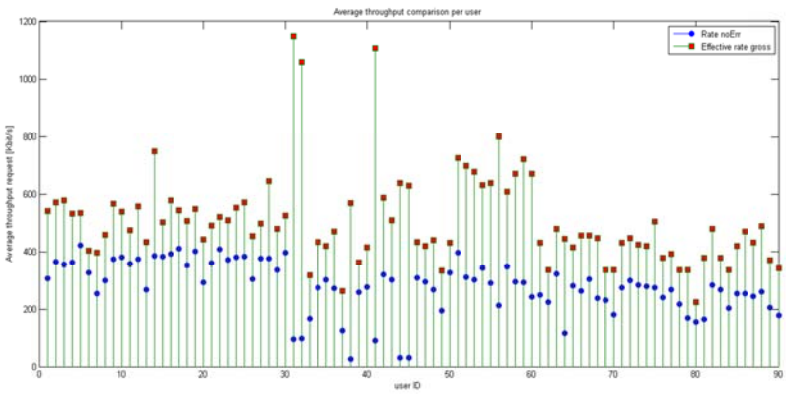


Figure 129. Traffic processing output. Left, comparison of traffic load per user. Right, zoom over the set of outdoor MUEs.

8.5.3 MBS offload by 30 FUEs on Femto network

The effect of attaching 30 indoor MUEs to a FAP has several outcomes, which are summarized in Table 18.

In this simulation, the FUEs have transmission power set to 15 dBm, while when they are MUEs it is 20 dBm, thus the overall power per user is reduced. The average power increase per user, due to the necessity to transmit NACK packets is significantly less than in other cases; the same is valid for the average power increase per user. Thus simulations confirm that FAPs allow MBS offload and ensure comparable or better transmission conditions to indoor users attached to them.

	MBS with 120 MUEs	**MBS with 90 MUEs**	**FEMTO layer 30 FUEs**
Traffic increase due to rescheduled packets	124 % [total]	97 %	58%
Overall Power expenditure [tot]/user	99.85 mW	99.85 mW	5.42 mW
Tx Power dBm	20	20	15
Average power increase – percentage/user	163.5 %	88.9 %	37%
Average power increase - mW/user	0.23 mW	0.13 mW	0.029 mW
Overall power increase	27.99 mW	11.42 mW	0.88 mW
30 usrs – overall power expenditure [tot] mW	748.9		329.2
Overall power expenditure/user mW	24.96		10.9
30 usrs – power increase – percentage/user	25.5 %		37.9 %
30 usrs - power increase - mW/user	0.036		0.036
30 usrs - Traffic increase due to rescheduled packets	89 %		53%
30 usrs - Traffic increase/user due to rescheduled packets (avg.)	2.9 %		1.95 %
90 usrs - overall power [tot]	26.9 mW		
90 usrs - power increase – percentage/user	210 %		
90 usrs - power increase - mW/user	0.299 mW		
90 usrs - Traffic increase due to rescheduled packets	140 %		
Flux tot - th MBps	6.1	4.3	1.0
Flux tot - out MBps	23.3	14.1	5.3
Flux tot - gross MBps	26.3	15.9	6.2

Table 18. Comparison of system performances when offloading the traffic of 30 MUEs and attaching them to FAPs.

9 CONCLUSIONS

The objective of this activity is to consider interference management and planning from a system level perspective, overcoming selfish approaches which can have an overall negative impact on the overall network. The methodologies implemented in this WP5 are considered in their impact on the business model for the scenarios considered. Clustering methods and strategies have been considered in their impact on the overall cell performances, allowing a faster convergence of optimization methods a providing a viable technique to improve network data flow. Complementarily to activity 5A1 (see Freedom-D51]), the metrics measuring system performances have also been extended to the case of variable band allocation and in a temporal varying environment.

These system-level simulations are preceded by an analysis of the femto-based interference impact, in the perspective of dense femto deployments. This analysis is realized with a LTE coverage simulator making simple MAC-layer abstraction (in particular, no inter-cell interference coordination is considered).

9.1 Technical conclusions

Downlink coverage simulation tools have been elaborated for characterization of the LTE macro+femto signal and interference levels based on the following methodology (Section 3): controlled or random large-scale FAP deployments in synthetic and real geographical environments; prediction of 3D path-loss maps; prediction of the LTE downlink coverage; and finally, estimate of the delivered throughput and network capacity. This approach was relevant in the frame of the FREEDOM studies; we think it could also be of interest for design, evaluation and optimization of operational two-tier networks, as an extension of usual radio-planning methods.

The simulation results (Section 8.1) give a characterization of:

- The FAP coverage and service improvement offered to a FAP customer;
- The FAP coverage and service improvement offered to any user, in case of an open-access mode FAP deployment;
- The degradation of the coverage (deadzone surface) and service performance suffered by a non FAP subscriber, in case of a closed-access FAP deployment.

This characterization is done at different scales, i.e. the considered user may be located in the same office or same house as the FAP; in the same floor as the FAP, or in the same building as the FAP; anywhere but indoors within the macro-cell; anywhere but outdoors within the macro-cell.

Results are mainly expressed as a statistical distribution of the available spectral efficiency. They are provided for three different deployment environments: urban corporate in presence of co-channel macro coverage (considering two inter-site distances 500m and 1732m); urban corporate in absence of co-channel macro coverage; and suburban residential. Besides, several analyses have been conducted to assess the impact of several deployment FAP parameters:

- Impact of the transmit power (10dBm or 20dBm) on the coverage and interference;
- Gain from a regular multi-FAP deployment compared to a random FAP deployment;
- Increase of the outdoor interference from a FAP deployment close to the external wall compared to deeper indoor deployment;
- Impact of the FAP traffic on the interference indoors and outdoors;
- Impact of the FAP density.

The main conclusions from all these simulations are summarized and employed in activity 6A2 for elaboration the engineering rules [FREEDOM-D62b].

The dynamic system simulator has been complemented including packet flow module to evaluate the information data passing through the cell and the impact of all transmitters on the QoS and energy needed to run a set of applications on UE mobile terminals.

The overall simulator has been tested in several cases of interest that can be summarized as:

- Impact of clustering on possibility to extend optimization methods at system level in a reliable way, in order to manage also high number of users;
- A set of real environments have been included, providing metrics also for a mapped scenario with geographic deployments of buildings and users;
- Mobility of users and temporal changes in the environment where transmitters are positioned have been included and evaluated;
- Evaluation on the system performances for different cases of varying band usage: equipartition of band between MBS and femto network, considering a fixed spectrum allocation for the MBS and varying that of second tier, or fixing the band usage of the femto network and increasing that of the macro network;
- Evaluation of system performances when including a GO for power assignment of FUEs/FAPs to mitigate indoor interference;
- Quantification of the MBS offload when routing traffic of a set of UEs indoor through FAPs instead of through the macro network.

9.2 *Impact on the business case*

This section summarizes the outcomes used in 2A3 activity for business model analysis. All inputs and key methodology aspects of the LTE coverage simulations presented in sections 9.2.1 to 9.2.4 are given section 3. These results are extension of those provided in section 8.1.

The development of some activities (clustering and optimization methods) developed in 3A2, evaluated at system level in 5A1 and 5A2 and their impact on the business case are reported in section 9.2.5. The overall conclusions that can be drawn from a list of simulations are also presented for their impact on possible choices for a MNO.

9.2.1 **Scenarios IA-1 and IA-2 – Impact on local urban corporate coverage**

Scenarios IA-1 and IA-2 evaluate the impact of a FAP deployment in one restricted urban corporate area (composed of a few buildings only) in presence of existing macro coverage.

Figure 130 gives spectral efficiency statistics for a FAP subscriber located into the same small 10m×10m area as the FAP. These statistics are compared to the spectral efficiency provided by the macro-only network. These figures will help a LTE network operator to assess the gain in quality of coverage it can offer to its corporate customers, in case a closed-access FAP is installed for subscribers located in a restricted area.

Remark that the simulation outputs are highly sensitive to the realized FAP deployments (generated from a random process); therefore only statistics given in one same table may be directly compared in order to assess gains or degradations in spectral efficiency.

Outage probabilities of spectral efficiency
- for a FAP subscriber located in the same 10m*10m area as the FAP
- considering a FAP ground-floor deployment in a 20m*80m wide building

	0.1 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
(a) Macro ISD = 500m, FAP located at range > ISD/3 from Macro BS				
Macro only	0%	44%	96%	100%
Reference FAP dplt [1]	0%	0%	3%	11%
FAP density 50%	0%	2%	9%	25%
FAP transmit power 10dBm	0%	0%	5%	21%
FAP activation ratio 100%	0%	1%	6%	21%
(b) Macro ISD = 1732m, FAP located at range > ISD/3 from Macro BS				
Macro only	0%	36%	94%	100%
Reference FAP dplt [1]	0%	0%	2%	5%
(c) Macro ISD = 500m, FAP located at range < ISD/3 from Macro BS				
Macro only	0%	18%	88%	100%
Reference FAP dplt [1]	0%	0%	10%	27%

Outage probabilities of spectral efficiency
- for a FAP subscriber located in the same 10m*10m area as the FAP
- considering a FAP deployment into a whole building (of random size)

	0.1 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
(a) Macro ISD = 500m, FAP located at range > ISD/3 from Macro BS				
Macro only	0%	58%	96%	100%
Reference FAP dplt [1]	0%	0%	2%	8%
FAP density 50%	0%	0%	4%	16%
FAP transmit power 10dBm	0%	0%	3%	15%
FAP activation ratio 100%	0%	0%	3%	13%
(b) Macro ISD = 1732m, FAP located at range > ISD/3 from Macro BS				
Macro only	0%	59%	98%	100%
Reference FAP dplt [1]	0%	0%	2%	7%

[1] FAP density 20%, transmit power 20dBm, activation ratio 50%

Figure 130: Scenarios IA-1 and IA-2 - Spectral efficiency offered to a corporate FAP subscriber into a small corporate area (10m×10m).

Figure 131 give similar results for a corporate FAP subscriber but considering here that this subscriber has access to all FAPs deployed within the corporate unit area. Two different corporate unit sizes are considered: one single building floor (the ground-floor actually) or the whole two neighbor buildings. These figures help a LTE network operator to assess the gain in quality of coverage it will offer to its corporate customers, in case several closed-access FAPs are deployed within the customer premises. Remark these same results apply to any user when FAPs are in open-access mode.

Outage probabilities of spectral efficiency
- for a corporate FAP customer[2] located anywhere within the ground-floor
- considering a closed-access FAP deployment in the ground-floor of a 20m*80m wide building

	0.1 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
(a) Macro ISD = 500m, FAP located at range > ISD/3 from Macro BS				
Macro only	0%	40%	98%	100%
Reference FAP dplt [1]	0%	18%	62%	75%
FAP density 50%	0%	11%	49%	67%
FAP transmit power 10dBm	0%	24%	74%	85%
FAP activation ratio 100%	0%	19%	65%	80%
(b) Macro ISD = 1732m, FAP located at range > ISD/3 from Macro BS				
Macro only	0%	56%	95%	100%
Reference FAP dplt [1]	0%	17%	44%	60%
(c) Macro ISD = 500m, FAP located at range < ISD/3 from Macro BS				
Macro only	0%	9%	84%	100%
Reference FAP dplt [1]	0%	5%	64%	85%

Outage probabilities of spectral efficiency
- for a corporate FAP customer[2] located anywhere in the building
- considering a closed-access FAP deployment into a whole building (of random size)

	0.1 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
(a) Macro ISD = 500m, FAP located at range > ISD/3 from Macro BS				
Macro only	0%	56%	96%	100%
Reference FAP dplt [1]	0%	5%	34%	61%
FAP density 50%	0%	0%	16%	43%
FAP transmit power 10dBm	0%	16%	56%	76%
FAP activation ratio 100%	0%	15%	82%	95%
(b) Macro ISD = 1732m, FAP located at range > ISD/3 from Macro BS				
Macro only	0%	58%	98%	100%
Reference FAP dplt [1]	0%	0%	14%	42%

[1] FAP density 20%, transmit power 20dBm, activation ratio 50%
[2] Apply also to any user if FAP access-mode is open

Figure 131: Scenarios IA-1 and IA-2 - Spectral efficiency offered to a corporate FAP subscriber (or any user if FAPs are in open-access mode) within the whole FAP deployment area.

Figure 132 give similar results but for a non-subscriber (i.e. a macro user) who is located within a FAP deployment in closed-access mode. These figures will help a LTE network operator to anticipate and control the degradation in quality of coverage that will be experienced by the non-subscribers.

Outage probabilities of spectral efficiency
- for an indoor non-subscriber located in ground-floor
- considering a closed-access FAP deployment in the ground-floor of a 20m*80m wide building

	0.1 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
(a) Macro ISD = 500m, FAP located at range > ISD/3 from Macro BS				
Macro only	0%	40%	98%	100%
Reference FAP dplt [1]	20%	60%	99%	100%
FAP density 50%	42%	76%	100%	100%
FAP transmit power 10dBm	12%	52%	99%	100%
FAP activation ratio 100%	34%	71%	99%	100%
(b) Macro ISD = 1732m, FAP located at range > ISD/3 from Macro BS				
Macro only	0%	56%	95%	100%
Reference FAP dplt [1]	30%	71%	96%	100%
(c) Macro ISD = 500m, FAP located at range < ISD/3 from Macro BS				
Macro only	0%	9%	84%	100%
Reference FAP dplt [1]	10%	24%	86%	100%

[1] FAP density 20%, transmit power 20dBm, activation ratio 50%

Outage probabilities of spectral efficiency
- for an indoor non-subscriber located anywhere in the building
- considering a closed-acess FAP deployment into a whole building (of random size)

	0.1 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
(a) Macro ISD = 500m, FAP located at range > ISD/3 from Macro BS				
Macro only	0%	56%	96%	100%
Reference FAP dplt [1]	46%	87%	99%	100%
FAP density 50%	76%	97%	100%	100%
FAP transmit power 10dBm	24%	77%	98%	100%
FAP activation ratio 100%	72%	96%	100%	100%
(b) Macro ISD = 1732m, FAP located at range > ISD/3 from Macro BS				
Macro only	0%	58%	98%	100%
Reference FAP dplt [1]	78%	96%	100%	100%

Figure 132: Scenarios IA-1 and IA-2 - Spectral efficiency offered to a non-subscriber (macro user) located within a corporate closed-access FAP deployment.

9.2.2 Scenarios IA-5 and IA-6 – FAP coverage in urban corporate area (no initial macro coverage)

Scenarios IA-5 and IA-6 evaluate the impact of a FAP deployment in one restricted urban corporate area (composed of a few buildings only) in absence of any macro coverage.
Scenarios IA-5 and IA-6 are the same as scenarios IA-1 and IA-2, except that MBS are not taken into account.

Figure 133 gives spectral efficiency statistics for a FAP subscriber located into the same small 10m×10m area as the FAP. Note that performances are the same as in scenarios IA-1 and IA-2 (i.e. in presence of macro coverage) since MBS do not impact coverage quality in these small areas.
These figures will help a LTE network operator to assess the gain in quality of coverage it can offer to its corporate customers, in case a closed-access FAP is installed for subscribers located in a restricted area in absence of any macro coverage.

Remark the simulation outputs are highly sensitive to the realized FAP deployments (generated from a random process); therefore only statistics given in one same table may be directly compared in order to assess gains or degradations in spectral efficiency.

Outage probabilities of spectral efficiency
- for a FAP subscriber located in the same 10m*10m area as the FAP
- considering a FAP ground-floor deployment in a 20m*80m wide building

	0.1 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
Macro only	100%	100%	100%	100%
Reference FAP dplt [1]	0%	0%	3%	11%
FAP density 50%	0%	2%	9%	25%
FAP transmit power 10dBm	0%	0%	5%	21%
FAP activation ratio 100%	0%	1%	6%	21%

Outage probabilities of spectral efficiency
- for a FAP subscriber located in the same 10m*10m area as the FAP
- considering a FAP deployment into a whole building (of random size)

	0.1 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
Macro only	100%	100%	100%	100%
Reference FAP dplt [1]	0%	0%	2%	8%
FAP density 50%	0%	0%	4%	16%
FAP transmit power 10dBm	0%	0%	3%	15%
FAP activation ratio 100%	0%	0%	3%	13%

[1] FAP density 20%, transmit power 20dBm, activation ratio 50%

Figure 133: Scenarios IA-5 and IA-6 - Spectral efficiency offered to a corporate FAP subscriber into a small corporate area (10m×10m).

Figure 134 give similar results for a corporate FAP subscriber but considering here that this customer has access to all FAPs deployed within the corporate unit area. Two different corporate unit sizes are considered: one single building floor (the ground-floor actually) or the whole two neighbor buildings.
These figures help a LTE network operator to assess the gain in quality of coverage it will offer to its corporate customers, in case several closed-access FAPs are deployed within the customer premises and in absence of any macro coverage.

Remark these same results apply to any user when FAPs are in open-access mode.

Outage probabilities of spectral efficiency
- for an indoor non-subscriber located in ground-floor
- considering a closed-access FAP deployment in the ground-floor of a 20m*80m wide building

	0.1 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
Macro only	100%	100%	100%	100%
Reference FAP dplt [1]	0%	13%	25%	41%
FAP density 50%	0%	0%	15%	42%
FAP transmit power 10dBm	4%	24%	39%	54%
FAP activation ratio 100%	2%	13%	32%	57%

Outage probabilities of spectral efficiency
- for an indoor non-subscriber located anywhere in the building
- considering a closed-acess FAP deployment into a whole building (of random size)

	0.1 bps/Hz	1 bps/Hz	3bps/Hz	5bps/Hz
Macro only	100%	100%	100%	100%
Reference FAP dplt [1]	0%	0%	11%	37%
FAP density 50%	0%	0%	10%	35%
FAP transmit power 10dBm	0%	0%	12%	39%
FAP activation ratio 100%	0%	0%	30%	62%

[1] FAP density 20%, transmit power 20dBm, activation ratio 50%

Figure 134: Scenarios IA-5 and IA-6 - Spectral efficiency offered to a corporate FAP subscriber (or any user if FAPs are in open-access mode) within the whole FAP deployment area.

9.2.3 Scenario IA-3 – Impact on urban network coverage

Scenario IA-3 evaluates the impact of a dense corporate FAP deployment in an urban network. Large-scale analyses are performed in real environments using site-specific models and 3D vector map data. The scenario is based on a downtown area of a European large city.

First result is the evolution of the total throughput from the original macro-only network toward the two-tier network (MBS+FAP), in open-access mode, considering a growing user demand, and a constant traffic load on the macro layout.

Figure 135 gives the network throughputs of the two-tier network for a FAP peak data rate higher than 3Mbps. These statistics are compared to the throughput provided by the macro-only network.
Figure 136 gives similar results for a peak data rate higher than 15Mbps. Peak data rates and throughputs take into account the physical layer overhead.

In the original macro only network, 36 users (active subscribers) are served with peak data rate of 256kbps and MBS traffic load TL=50%. The user activation ratio is 4.7%.
In the two-tier network, we make distinction between two different user profiles: low data rate users who require 256kbps and are uniformly spatially distributed; and high data rate users who require more than 3Mbps or 15 Mbps and are located in the close FAP vicinity (in same 10m×10m area). We assume the deployment of FAPs encourages the use of high data rate mobile services (i.e. simulated FAP activation ratios are 10% and 20%) in its close vicinity. Besides, the macro offload and presence of open-access FAPs in the environment permit an increase in the usage of low data rate services anywhere in the cell.

We get the two following results:

- The average amount of data delivered by a FAP to high data rate users is greater than 1Gb/hour and peak data rate is more than 3Mbps:
    - For this high data rate usage, the FAP activation ratio and the FAP traffic load are fixed to 10%.

- The number of active high data rate users reaches 10, 20 or 40 (depending on the scenario), without any significant impact on the global macro service coverage.
- The number of active low data rate users increase from 36 (in macro-only network) to 43 or 44, with about 15% served by the FAPs.
- See all results in Figure 135.

• The average amount of data delivered by a FAP to high data rate users is greater than several Gb/hour and peak data rate is more than 15Mbps:
  - For this high data rate usage, the FAP activation ratio is fixed to 10% and the FAP traffic load to 50%.
  - Observations are similar to previous ones, as the interference generated from the active FAPs has still a very limited impact on the global macro performance.
  - See all results in Figure 136.

Open-access mode - FAP users with high data rate > 3Mbps

	Active users with high data rate (FAP users)		Active users with low data rate (FAP/Macro users)				Throughput (Mbps)			Cover rate	
	# users	Data rate (kbps) [1]	# MBS users	# FAP users	# total users	Data rate (kbps)	FAP	MBS	Total network	Indoor	Outdoor
Macro only	-	-	36	-	36	256	-	9.2	9.2	100%	100%
Two-tier:											
FAP density 10% Activat. ratio 10%	10	3259	37	6	43	256	34.1	9.5	43.6	100%	100%
FAP density 20% Activat. ratio 10%	20	3259	37	7	44	256	67.0	9.5	76.5	100%	100%
FAP density 20% Activat. ratio 20%	40	3259	37	7	44	256	132.2	9.5	141.7	100%	100%

[1] Minimum net throughput to be delivered by the FAP internet access.

Figure 135. Macro only and two-tier network throughputs - FAP high data rate > 3Mbps – Open-access.

Open-access mode - FAP users with high data rate > 15Mbps

	Active users with high data rate (FAP users)		Active users with low data rate (FAP/Macro users)				Throughput (Mbps)			Cover rate	
	# users	Data rate (kbps) [1]	# MBS users	# FAP users	# total users	Data rate (kbps)	FAP	MBS	Total network	Indoor	Outdoor
Macro only	-	-	36	-	36	256	-	9.2	9.2	100%	100%
Two-tier:											
FAP density 10% Activat. ratio 10%	10	16294	37	6	43	256	164.5	9.5	174.0	100%	100%
FAP density 20% Activat. ratio 10%	20	16294	37	7	44	256	327.7	9.5	337.2	100%	100%
FAP density 20% Activat. ratio 20%	40	16294	37	7	44	256	653.6	9.5	795.3	100%	100%

[1] Minimum net throughput to be delivered by the FAP internet access.

Figure 136. Macro only and two-tier network throughputs - FAP high data rate > 15Mbps – Open-access.

Second result is based on the same scenario and same user profiles, but in closed-access mode. The low data rate users are assumed to be non-FAP subscribers and can thus only be attached to MBS. Simulation results are given for 10% FAP density (462 FAPs/km² or 0.13 FAP/subscriber) and 10% FAP activation ratio. They can be compared to the first two-tier network performance presented in Figure 135 and Figure 136 for open access mode. We get similar delivered throughput to FAP high data rate users; however the number of low data rate users is limited to 36 as in the original macro-only network. Besides the macro coverage is degraded in the vicinity of the FAPs delivering high data rate.

Closed-access mode - FAP users with high data rate > 3Mbps or 15Mbps

	Active users with high data rate (FAP users)		Active users with low data rate (Macro users)		Throughput (Mbps)			Macro cover rate	
	# users	Data rate (kbps) [1]	# MBS users	Data rate (kbps)	FAP	MBS	Total network	Indoor	Outdoor
Macro only	-	-	36	256	-	9.2	9.2	100%	100%
Two-tier:									
FAP traffic load 10% High data rate > 3Mbps	10	3246	36	256	32.5	9.2	41.7	98%	100%
FAP traffic load 50% High data rate > 15Mbps	10	16230	36	256	162.3	9.2	171.5	97%	99%

[1] Minimum net throughput to be delivered by the FAP internet access.

Figure 137. Macro only and two-tier network throughputs - FAP high data rate > 3Mbps or 15Mbps – Closed-access.

Third result is the evolution of the macro downlink traffic load, considering a constant user demand, i.e. constant number of users and constant total throughput in the network service area. Only the FAP deployment with 10% FAP density (462 FAPs/km² or 0.13 FAP/subscriber) and open-access mode has been simulated.

A constant network throughput shown in Figure 138 is obtained for a FAP downlink traffic load of 1% with FAP activation ratio 10%. The macro downlink TL is reduced from 50% to 23%, meaning that 27% of the macro network capacity is offloaded.

Open-access mode - Constant user demand

	Active users with low data rate (FAP/Macro users)				Throughput (Mbps)			Cover rate		Traffic load per base-station	
	# MBS users	# FAP users	# total users	Data rate (kbps)	FAP	MBS	Total network	Indoor	Outdoor	FAP	MBS
Macro only	36	-	36	256	-	9.2	9.2	100%	100%	-	50%
Two-tier: FAP density 10% FAP activ. ratio 10%	26	10	36	256	2.5	6.7	9.2	100%	100%	1%	23%

Figure 138: Macro only and open-access two-tier network for a constant traffic demand.

9.2.4 Scenario IA-4 – Impact on suburban network coverage

Scenario IA-4 evaluates the impact of a dense residential FAP deployment in a suburban network.
First result is the evolution of the total throughput from the original macro-only network toward the two-tier network (MBS+FAP), in open-access mode, considering a growing user demand, and a constant traffic load on the macro layout.

Figure 140 gives the network throughputs of the two-tier network for a FAP peak data rate higher than 3Mbps and 15 Mbps (obtained respectively with FAP traffic load 10% and 50%). These statistics are compared to the throughput provided by the macro-only network.

In the original macro-only network, 18 users (active subscribers) are served with peak data rate of 256kbps and MBS traffic load TL=50%. The user activation ratio is 3.0%.
In the two-tier network, we make distinction between two different user profiles: low data rate users who require 256kbps and are uniformly spatially distributed; and high data rate users who require more than 3Mbps or 15 Mbps and are located in the close FAP vicinity (same 24m×24m house area). We assume the deployment of FAPs encourages the use of high data rate mobile services (i.e.

simulated FAP activation ratio is 10%) in its close vicinity. Besides, the macro offload and presence of open-access FAPs in the environment permit an increase in the usage of low data rate services anywhere in the cell.

We get the two following results:

- The average amount of data delivered by a FAP to high data rate users is greater than 1Gb/hour and peak data rate is more than 3Mbps:
  - For this high data rate usage, the FAP activation ratio and the FAP traffic load are fixed to 10%.
  - The number of active high data rate users reaches 10.
  - The number of active low data rate users increase from 18 to 68, with about 65% served by the FAPs. The activation ratio for this low data rate usage increases from 3.0% to 13.0%.
  - The percentage of users served by the FAPs is high in this scenario, as half network subscriber houses are assumed to have a FAP; furthermore some FAPs provide service to neighbor houses.
  - See all results in Figure 139.

- The average amount of data delivered by a FAP to high data rate users is greater than several Gb/hour and peak data rate is more than 15Mbps:
  - For this high data rate usage, the FAP activation ratio is fixed to 10% and the FAP traffic load to 50%.
  - The number of active high data rate users reaches 10.
  - As the macro coverage is locally degraded, the percentage of low data rate users served by the FAP increases compared to the previous result: from 65% to 68%.
  - See all results in Figure 139.

Second result is based on the same scenario and same user profiles, but in closed-access mode. We get similar delivered throughput to FAP high data rate users. However the number of low data rate users is limited to 23 or 25: the number of users served by the MBS is quite similar to the one in the macro-only network, while the closed-access FAPs provide low data rate service only to the users likely to be a subscriber (i.e. users located in the same 24m×24m house area). The activation ratio of low data rate users increases from 3.0% (in macro-only network) to 5.5% or 5.8%.

Note that the macro coverage is degraded in the vicinity of the FAPs delivering high data rate so that "dead zones" appear.

Open-access mode - FAP users with high data rate > 3Mbps or 15Mbps

	Active users with high data rate (FAP users)		Active users with low data rate (FAP/Macro users)				Throughput (Mbps)			Cover rate	
	# users	Data rate (kbps) [1]	# MBS users	# FAP users	# total users	Data rate (kbps)	FAP	MBS	Total network	Indoor	Outdoor
Macro only	-	-	18	-	18	256	-	4.6	4.6	100%	100%
Two-tier:											
Traffic load 10% High data rate > 3Mbps	10	3312	24	44	68	256	44.4	6.1	50.5	100%	100%
Traffic load 50% High data rate > 15Mbps	10	16614	23	49	72	256	178.6	5.9	184.5	100%	100%

[1] Minimum net throughput to be delivered by the FAP internet access.

Figure 139. Macro only and two-tier network throughputs - FAP high data rate > 3Mbps or 15Mbps – Open-access.

Closed-access mode - FAP users with high data rate > 3Mbps or 15Mbps

	Active users with high data rate (FAP users)		Active users with low data rate (FAP/Macro users)				Throughput (Mbps)			Cover rate	
	# users	Data rate (kbps) [1]	# MBS users	# FAP users	# total users	Data rate (kbps)	FAP	MBS	Total network	Indoor	Outdoor
Macro only	-	-	18	-	18	256	-	4.6	4.6	100%	100%
Two-tier:											
Traffic load 10% High data rate > 3Mbps	10	3292	17	6	23	256	34.4	4.4	38.8	98%	100%
Traffic load 50% High data rate > 15Mbps	10	16551	18	7	25	256	167.3	4.6	171.9	94%	99%

[1] Minimum net throughput to be delivered by the FAP internet access.

Figure 140. Macro only and two-tier network throughputs - FAP high data rate > 3Mbps or 15Mbps – Closed-access.

9.2.5 Impact of methodologies at system level

The simulations performed so far, confirm how the indoor environment has the less performing transmission conditions for UEs. Moreover, although deployment of FAPs can overcome such situation, the additional interference introduced in the system is one of the major drawbacks for indoor MUEs. This situation is even worsened when inside buildings there is a FAP deployment interfering with it.

Power and spectrum management have been demonstrated to be relevant parameters that can be considered by a MNO to improve network performances. Since transmissions are in licensed bands, operators can adopt different strategies to maintain average QoS. Implementation of different methodologies for resources optimization imposes some constraints on spectrum usages that must be considered from a business point of view and which apply with differences from one scenario to another, especially depending on transmitter's density.

In this view, simulations show how a modest management of transmission power can be implemented at system level, allowing reducing power consumption and significantly improving overall network performances, both in terms of average throughput per user per PRB, and in terms of outage. Indeed, the methodologies exposed in this activity show how management of the spectrum and/or transmission power allow gaining a better system performance. Indeed, clustering strategies open the way to fast management of resources by different optimization methods.

Transmission power can be assigned with a set of criteria (minimum power, adapted power, optimized power) and similarly the spectrum can be partitioned in different ways (by assigning maximum bandwidth usage to FAPs in a rigid or adaptive way) such that overall experience of users is improved, both for FUEs and, moreover, for MUEs, which are the ones most suffering from indoor interference.

Different types of band partition have been analyzed and offer to a MNO several means to manage and reduce interference, improving QoS and traffic flow.