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3D coverage analysis of LTE urban heterogeneous networks with dense femtocell deployments

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Abstract

Femtocell technology recently gained attention due to its potential benefits for mobile operators (significant capacity offload and extension of the coverage at low cost) but there are still hard technical challenges to be addressed (e.g., the optimization of the interference management). Furthermore, the deployment strategies are still in question, such as the femtocell access-mode (open or closed) and the spectrum usage to adopt. Consequently, reliable simulations are necessary in the perspective of massive femtocell deployments, in particular for characterization of the impact on the coverage quality. An original solution is introduced and exploited in this article. It offers two complementary approaches for two different applications: a synthetic model for realization of small-scale or illustrative case studies and a real model for realistic and large-scale heterogeneous network performance evaluation. It relies on a suite of simulation tools including the generation of random 3D femtocell deployments in synthetic or real environments; realistic pathloss predictions; and a 3D downlink coverage performance analysis (i.e., considering all floors) of long-term evolution heterogeneous networks. A first study shows not only a large improvement of coverage quality for femtocell users, but also a very significant degradation for *non-subscribers* in the vicinity of closed-access femtocells. The femtocells have a strong impact locally (gain or degradation depending on the access-mode and user type) and not only at their own floor. Therefore, a 3D evaluation is relevant. Then, a second study offers realistic and large-scale analyses of the coverage evolution after corporate femtocells have massively been deployed in urban macrocells. The results show a moderate impact on the average spectral efficiencies but a strong impact locally. In this study, closed-access femtocells cause dead zones for *non-subscribers* in 15% of indoor areas leading to non-uniform service coverage, whereas they increase the spectral efficiency of *femtocell subscribers* (by 1.5 bps/Hz in 20% of indoor areas). These are critical information for a mobile operator since the experience of its customers is much affected by the femtocell deployment and by the selected access mode.

Keywords: Access mode, FAP, Femtocells, Heterogeneous network, LTE, Interference, SINR, Spectral efficiency, Propagation model

Introduction

Large-scale deployment of femtocell access points (FAPs) into 3 G networks today and 4 G networks in the very near future is expected to generate a large amount of capacity offload that will help wireless operators to answer to the huge data traffic growth that is being experienced since commercialization of smart phones. It seems that femtocell technology is setting up among usual network solution equipments, as reference [1] announces up to 36 commercial launches of UMTS or CDMA services over the globe in October 2011; the same source expects about 48 million FAPs by 2014. In addition to significant capacity offload allowed by the massive installation of residential or corporate FAPs, the benefits for the operator might be an extension of the coverage at low cost in terms of CAPEX and OPEX, and finally a reduction of the churn rate. On the customer point of view, femtocells must ensure high-quality coverage, high throughput, and the appearance of new services requiring high data rate and possibly localization. The presence of femtocells in some operator commercial portfolios is today a major selling proposition and participates in the commercial competition.

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Even though the femtocells are now part of the 3GPP, 3GPP2, and WiMAX standards, there are still hard technical challenges that prevent a two-tier network with dense FAP deployments to be efficiently operational. The major one is the optimization of the interference management, as a FAP locally generates a strong signal strength that may interfere with communications in the macrocell or neighbor femtocells. Robustness to the backhaul latencies and adaptation to the backhaul throughput constraints are other key technical issues, as well as the elaboration of efficient handover algorithms working in an environment composed of unmanaged, small, and dense cells.

The deployment strategies and to whom should be given the access to the FAPs are in question. First, two basic possible access modes exist. The open-access mode allows any user to connect the FAP. Thus, the network coverage and the throughput are significantly improved in the FAP vicinity, but at the cost of higher security rules and robust handover techniques, and at the condition that the FAP customer accepts sharing its FAP and internet resources. The closed-access mode authorizes only a limited set of subscribing users (in Closed Subscriber Group—CSG) to connect the FAP, thus the customers get exclusive and full benefit from its FAP, but interference on other neighbor users is strong. Hybrid access [2] might be a solution to efficiently increase offloading and reduce the interference level (compared to the closed-access mode), whereas the FAP customer keeps a privileged access. Specific signaling is required and must be optimized. To the best of authors' knowledge, no such solution is available today in the equipments. Other strategy questions are about the spectrum usage or resource partitioning, and about competition with another low cost and widespread high data rate technologies, i.e., Wi-Fi.

Consequently, the elaboration of robust and realistic business models is essential for operators investigating the opportunity to launch FAP deployments. A study realized by the ICT-BeFemto project [3] shows that a financial benefit is always obtained whatever the business model is: one-off fee (the customer pays for the equipment and pays a monthly fee), decreased monthly fee, increased monthly fee, or free. The fee must be adjusted to attract customers and make the penetration ratio increase.

The history of the femtocell market is short and the range of possible strategies is large. Reference [1] stresses the free femtocell offer launched from SFR in France in 2011. Furthermore, the growing corporate deployment segment provides a service with a high upfront fee. In this case, the installation is done by the operator and FAP capabilities are superior, which justify the higher fee.

Simulations are necessary in the perspective of massive FAP deployments, in particular for the characterization of femtocell interference, the evaluation of interference mitigation techniques, the evaluation of the capacity offloading, as well as the creation of relevant inputs to the business models. Many results have been published already. The Small Cell Forum (formerly FemtoForum) proposes interference analysis based on pathloss predictions and case study simulations realized at system-level, for both UMTS [4] and OFDMA [5]. System-level simulations with simple pathloss models are used as well to investigate the macrocell offloading benefits in noise-limited or interference-limited network [6] or the performance of interference mitigation techniques [7,8]. An FDTD propagation model is employed in [9] to evaluate the performance of a hybrid-access method in a 2D residential scenario. Namgeol et al. [10] employs a more detailed propagation environment to analyze the coverage of a single FAP. However, all these results are based on 2D synthetic environment models that cannot fully represent signal and interference levels generated by FAPs, especially in neighbor floors and buildings. Furthermore, they focus only on global analysis (i.e., on a macrocell scale) or on analysis at whole FAP deployment floor. To the best of the authors' knowledge, neither detailed 3D spatial analysis nor global analysis in real environments has been published.

The authors extended the usual radio-planning simulation tools and methodology to assess heterogeneous network coverage performance in realistic dense long-term evolution (LTE) FAP deployment scenarios. First, it relies on the generation of random 3D FAP deployments and realistic pathloss models especially for the FAP indoor-to-outdoor scenario [11]. Two complementary approaches for two different applications are proposed: a synthetic model for realization of small-scale or illustrative case studies and a real model for realistic and large-scale two-tier network performance evaluation. Then, LTE downlink metrics, namely signal-to-interference-plus-noise ratio (SINR) and spectral efficiency, are simulated and statistics are extracted from the coverage map analysis. The novelty mainly lies into the integration (partly random) of the femtocell layout into a synthetic or real macro network and into the 3D aspect, as the coverage maps are calculated in streets and in different building floors. Furthermore, both open- and closed-FAP access modes and different user types (*FAP subscriber, non-subscriber*) are handled.

This suite of simulation tools was mostly elaborated in the frame of the European funded ICT-FREEDOM project [12] that investigates future femto-based networks and examines solutions allowing large femtocell deployments in OFDMA networks. The studies reported hereafter consider the introduction of dense

FAP deployments in corporate buildings within an existing urban macrocell LTE FDD network that provides service coverage everywhere but limited capacity. Simulations are conducted at a frequency of 2.0 GHz for downlink only. They lead to a 3D assessment of the impact on coverage performance of FAP deployments, locally, i.e., in the vicinity of FAPs, at deployment and neighbor floors, in surrounding streets and in neighbor buildings; and globally at network coverage level, indoors, and outdoors. Both open- and closed-access modes and *FAP subscribers* and *non-subscribers* are addressed. Thereby, this article offers a detailed analysis of FAP deployments impact at different scales in realistic LTE heterogeneous network scenarios and with a refined propagation modeling.

The article is organized as follows. "Pathloss models" section presents the pathloss models involved in the simulations, with a particular focus on the models elaborated for the indoor-to-outdoor propagation scenario. "Simulation methodology for LTE network coverage" section describes the global simulation methodology to obtain statistics on the LTE coverage performance. Results are given in "Simulation results" section. A first study analyzes the impact of a FAP deployment in one single building floor. A second study evaluates the coverage evolution after corporate FAPs have massively been deployed in urban macrocells. Finally, "Conclusion" section summarizes the main outcomes of this contribution.

Pathloss models

Overview

The first brick in the LTE coverage simulations is the prediction of pathloss matrices. This requires the pathloss models to be able to address in a coherent way all radio link situations found in heterogeneous networks combining macro base stations and FAPs. Two complementary approaches have been employed in this study.

On the one hand, analytical models associated to a synthetic representation of the environment permit the realization of illustrative case studies and comprehensive characterizations of the FAP deployment impact. Analysis of the network performance can be performed into a limited area composed of a few buildings where FAPs are deployed. It enables to assess the evolution of network coverage metrics in the femtocell, at deployment floor and neighbor floor, in the buildings, etc.

On the other hand, realistic and large-scale analyses are performed in real environments using a site-specific model originally developed for radio-planning tasks. This approach enables realistic evaluation of a two-tier network composed of an urban typical macro layout and a dense FAP deployment. The usage of high-resolution geographical map data and a site-specific propagation model bring realistic spatial correlation and variability in pathloss predictions. This second approach also represents a proof-of-concept for simulation tools adapted to a large-scale two-tier network evaluation.

For the first approach (synthetic environment model), the set of selected analytical models is as follows.

- From macro-BS (base station) to outdoor user: ITU-R P.1411-5 recommendation [13], actually based on the COST231 Walfish-Ikegami model, considering a 15-m building height, 20-m street width, and 50-m inter-building distance on average.
- From macro-BS to indoor user: application of a 2-dB/floor gain below the average building height and penetration method from the COST231 building penetration model [14].
- From FAP to close indoor user: COST231 multi-wall model [14].
- From FAP to outdoor or neighbor-building user: original approach presented below.

For the second approach (real environment model), the selected site-specific model is the ray-based Volcano by SIRADEL [15], whose main mechanisms are described in [16]. It is able to simulate multiple propagation paths in a complex environment with reduced computation times. This tool gathers many heuristic parameters obtained from many years of engineering experience and drive testing for many wireless operators around the world. Consequently, the prediction model could be understood as pre-calibrated. Nevertheless, this study has taken benefit for a more specific calibration, since a large amount of measurements were available in the study environment (Paris at 2.0 GHz).

In both cases, analytical and site-specific, the prediction of the pathloss from the FAP to surrounding streets and buildings is a key and challenging issue. Thus, a particular attention was brought by the authors to the evaluation and also elaboration of the models addressing this situation. For this purpose, CW vertically polarized power measurements have been carried out at 2.1 GHz in a medium-size European city. The transmitter that represents the FAP is installed in different configurations (close to window, light indoor, and deep indoor), in two distinct environments (office building in suburban: average street width 10 m and average building height 25 m, historical-like building in dense urban: average street width 35 m and average building height 10 m), and two different floors (ground floor and first floor). The received power is collected in the surrounding streets. Exploitation of these measurements is shortly reported in next sections, however details may be found in [11].

Presentation of the site-specific pathloss model

The site-specific model is the urban ray-tracing described in [16]. The 3D outdoor trajectory of rays is simulated from multiple interactions with the buildings (reflections and diffractions) and other obstacles (vegetation or ground). Indoor-to-outdoor (and resp. outdoor-to-indoor) rays are assumed to propagate along a straight horizontal trajectory inside the floor that contains the base-station (resp. user). The indoor loss accounted for calculation of the received field is the sum of:

- an average indoor–outdoor interface loss (10 dB in this study),
- a loss depending on the outdoor vertical incidence angle, and
- a statistical loss depending on the indoor path length (1.2 dB/m in this study).

The evaluation of this ray-tracing by comparison to all measurement scenarios gives a standard deviation of 8.5 dB for the error. This result is very good, considering that the propagation environments are complex, varied (involving two distinct buildings, two distinct urban densities, and three distinct FAP locations), and with no representation of the building internal walls and openings.

An enhanced version of this model was presented in [11] leading to more realistic local variations and significant reduction in the mean error sensitivity. The main modification consists in the introduction of multiple paths diffracted at the window edges.

Elaboration of the analytical indoor–outdoor pathloss model

The proposed analytical model is inspired by the COST 231 building penetration method [14] but applied reversely. The pathloss is estimated by the dominant contribution calculated among all paths propagating in directions perpendicular to the building exterior walls, as illustrated in Figure 1. Remarking the geometric construction of this dominant contribution does not generally coincide with a physical propagation path but is a simple empirical solution providing a realistic mean pathloss.

The mean pathloss is calculated as follows

$$PL = PL_{MICRO} + W_E + WG_E(1 - sin\theta)^2 + 0.7d_{IN} + L_W q_W \quad (1)$$

where $L_W = 5$ dB is the loss through apartment or office separations; q_W is the number of apartment or office separations along the dominant path; d_{IN} is the indoor horizontal path-length (in meters), along the dominant path; θ is the incidence angle on the external wall, $sin\ \theta = D \div d_{OUT}$; D is the 2D outdoor distance (in meters), measured in the direction perpendicular to the external wall; d_{OUT} is the 3D outdoor path-length (in meters), $W_E = 7$ dB is the penetration loss for normal incidence (i.e., $\theta = 90°$); and $WG_E = 20$ dB is the additional loss for grazing incidence (i.e., $\theta = 0°$).

PL_{MICRO} is the outdoor propagation losses. Its formulation at frequency 2.1 GHz is derived from the above-mentioned CW measurements [11]:

$$LOS : PL_{MICRO} = 38.4 + 21.5\log10(d_{IN} + d_{OUT}) \quad (2)$$

$$NLOS\ sub : PL_{MICRO} = 17.0 + 40.0\log10(d_{IN} + d_{OUT}) \quad (3)$$

$$NLOS\ dense\ urb : PL_{MICRO} = 6.5 + 50.0\log10(d_{IN} + d_{OUT}) \quad (4)$$

LOS (resp. NLOS) occurs when the indoor-to-outdoor point is in line-of-sight (resp. non-line-of-sight) from the outdoor terminal.

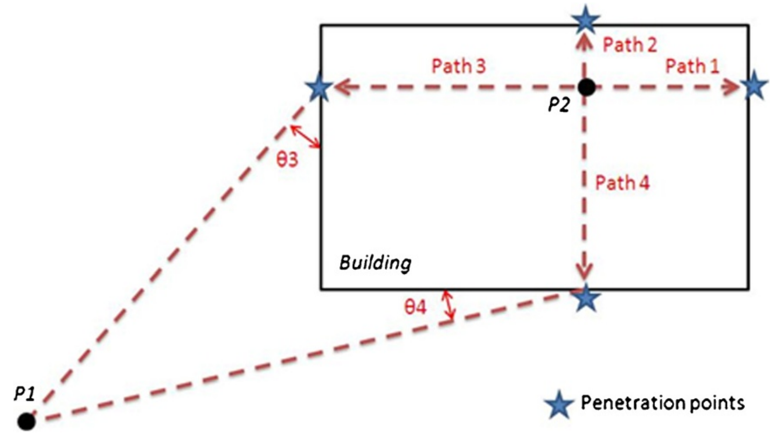

Figure 1 Determination of the dominant path in the analytical model.

Extension to the analytical indoor–outdoor–indoor scenario

The indoor–outdoor–indoor extension is constructed from assumption that the outdoor–indoor propagation mechanisms are symmetrical to indoor–outdoor ones. The pathloss is the sum of the five following components: indoor loss in the FAP building; indoor-to-outdoor interface loss at the FAP building facade; LOS or NLOS outdoor loss; outdoor-to-indoor interface loss at the user building facade; and indoor loss in the user building. The dominant path is determined after testing all possible combinations of indoor–outdoor or outdoor–indoor interface points.

Simulation methodology for LTE network coverage

This section presents the simulation tools, methodology, and assumptions for the analysis of the network coverage and interference considering dense femtocell deployments. The effective SINR on downlink (DL) data channel is calculated over a 3D pixel grid that represents all possible locations of users, i.e., 2D pixel grid that is usually computed in coverage analysis is extended to multiple floor reception. The SINR at location (x, y, z) and served by the BS i is given by

$$\mathrm{SINR}_i(x,y,z) = \frac{P_{rx,i}(x,y,z)}{\Sigma_{j\neq i}\eta_j P_{rx,j}(x,y,z) + N_0} \tag{5}$$

where $P_{rx,i}$ is the received power from the BS i (in W), η_j the traffic load (TL) of the BS cell j in the range from 0 to 100% and N_0 the noise (in W). The calculation relies on a simple abstraction of the MAC layer protocols, where the interference from cell j is given by weighting the received power $P_{rx,j}$ by the DL traffic load η_j. This traffic load represents the average portion of signal resources allocated to the cell users. And the sets of resource blocks allocated by two different cells are assumed to be random and independent. The traffic load of a cell is a critical simulation input, as the interference levels and the coverage quality directly depend on it. Average loads of macro- and femtocells are used in this article and thus no user distribution is needed. However the traffic loads might have been fine-tuned for each cell to take into account the spatial distribution of traffic.

Finally, the maximum available spectral efficiency is given by an SINR mapping table [17]. Multi-antennas are employed here only for diversity gain, thus spectral efficiency enhancement from spatial multiplexing is not considered.

Other main simulation parameters are given in Table 1.

Table 1 Main simulation parameters

Category	Parameter values
System	LTE FDD
	2 × 10 MHz.
	Central frequency: 2.0 GHz
Macro layout	Three sectors per site
	Hexagonal site deployment: two rings around the central site, i.e., 19 sites corresponding to 57 cells (see Figure 3)
	Inter-site distance (ISD): 500 m
	Average antenna height: 32 m above ground
	Maximum transmit power per antenna: 46 dBm
	Antenna: directional, 14 dBi gain
	Antenna elect. down-tilt: 6°
	Number of antennas per sector: 4
Femto layout	One sector per site
	Spectrum usage: co-channel
	Access modes: open/closed
	Antenna height: 1 m above floor
	Maximum transmit power: 20 dBm
	Antenna: omnidirectional: 5 dBi gain
	Number of antennas: 2
User	UE antenna height: 1.5 m above ground
	UE antenna: omnidirectional: 0 dBi
	UE number of antennas: 1
	UE noise figure: 9 dB
	User types: FAP subscriber/corporate FAP subscriber/non-subscriber

The simulation workflow is divided into three successive steps as illustrated in Figure 2. 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 3. Then, N random FAP deployments are generated into building floors within the three central cells plus a 100-m margin.

In the first study, based on a synthetic environment model (i.e., buildings are represented by rectangular blocks separated by a 20-m wide street, as shown in Figure 4), the buildings are randomly dropped in the study area. The second study considers deployment of corporate FAPs into a real environment representation. Corporate buildings where FAPs are installed are randomly selected among the buildings located in the study area to reach a ratio of 20%. In both studies, buildings are divided into 100 m^2 small areas, where at most one FAP is authorized to be installed. Then, it is randomly defined if a small area has a FAP or not, depending on a FAP density, i.e., the percentage of small areas owning a FAP. Finally, the locations of FAPs within their small area is generated from a random uniform distribution law. Small areas with a FAP are called FAP areas.

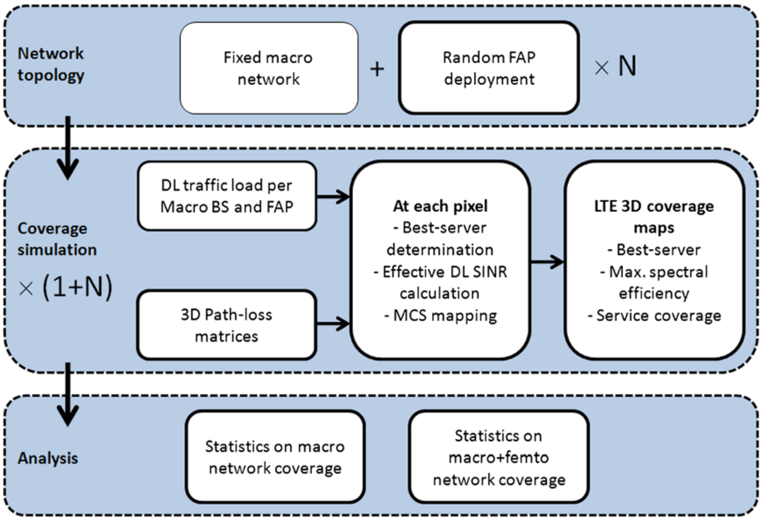

Figure 2 Simulation and analysis procedure.

A FAP is not necessarily active, meaning that there may be no user in communication with this FAP (its traffic load is null), except the user for which the coverage is simulated. The activation of a FAP is random, based on an average activation ratio in the range from 0 to 100%.

Coverage is simulated in the second step from, respectively, the macro-only network and the *N* random

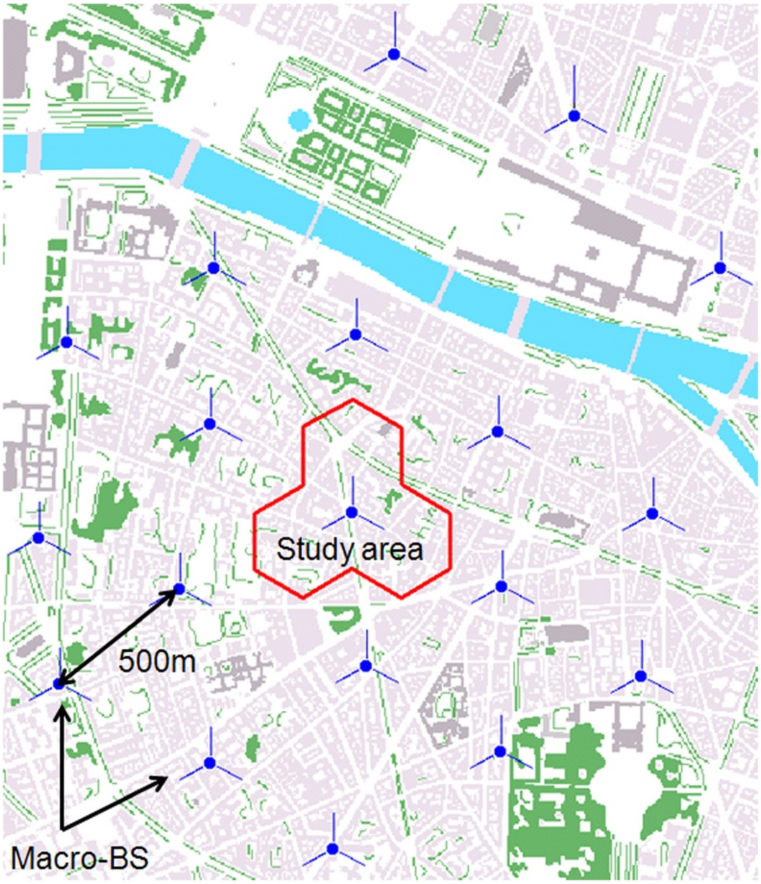

Figure 3 Scenario 2—macro layout and study area.

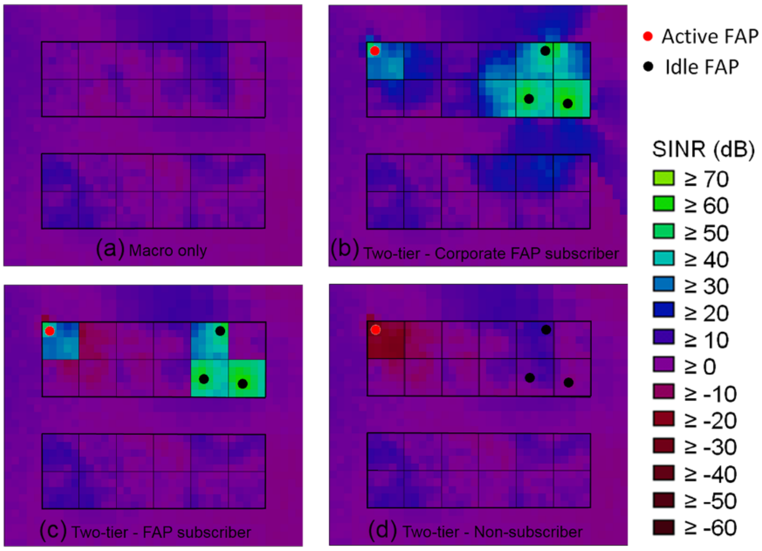

Figure 4 **Scenario 1—SINR maps at the ground floor.**

two-tier networks. Outputs are 3D maps providing the service coverage area, the best-server, and the available spectral efficiency at any possible user locations in the streets and in building floors. As an example, Figure 5 shows spectral efficiency maps at third floor of a macro-only network and a two-tier network with FAPs in a real environment. Note that for clarity, only FAPs of the third floor are displayed but the impact of FAPs deployed at neighbor floors is visible.

Both open- and closed-FAP access modes and three user types are handled:

- *FAP subscriber*, who is located in a 100-m^2 small area with a FAP, the so-called FAP area;
- *Corporate FAP subscriber*, who is located anywhere and is part of all FAP CSG. It is equivalent to the situation for a *non-subscriber* when all FAPs are in open-access mode;
- *Non-subscriber*, who is located anywhere and is not part of any FAP CSG.

A random spatially correlated lognormal component, which represents the unpredicted or mis-predicted part of the shadowing, is added to the predicted mean pathloss. This approach is very common when using an analytical pathloss model. This is not true for site-specific pathloss predictions employed in radio planning tasks, where prediction errors and unpredicted shadowing variations are compensated by the addition of a margin that gives a certain level of confidence to the result. However, this study aims at characterizing the network performance evolution from the macro-only to the two-tier network topology; this

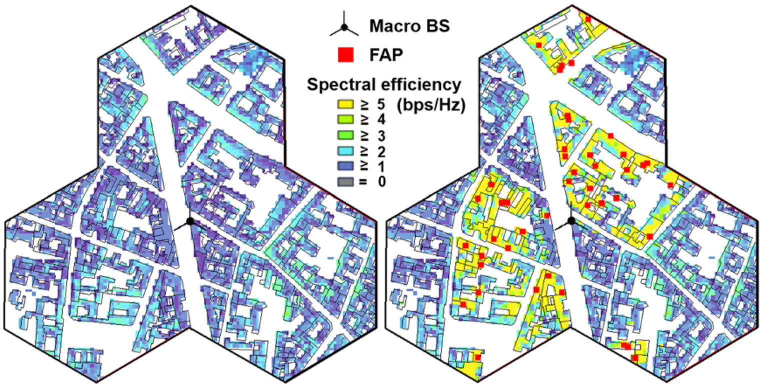

Figure 5 **Spectral efficiency maps at third floor of a macro-only network and a two-tier network with FAPs in a real environment.**

would have partially been masked by the use of a margin.

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

Simulation results

Local impact of a FAP deployment on network coverage

The impact of a single-floor FAP deployment in one restricted urban corporate area (composed of two buildings as shown in Figure 4) is evaluated in the presence of existing macro coverage. The simulations are carried out with the synthetic environment model and the analytical propagation models to get a comprehensive characterization of the local impact of a FAP deployment. The scenario is described in Tables 1 and 2. These parameters are always applied, unless otherwise mentioned.

SINR maps analysis

The local impact of FAPs on SINR maps may be observed from each run among the random FAP deployments and random shadowing process. The example in Figure 4 shows SINR maps from one run simulated at the ground floor of two buildings from three idle FAPs and one active FAP deployed at the ground floor of one of these buildings. The SINR levels of the macro-only network ranges from −5 to 20 dB. The SINR levels for *corporate FAP subscribers* in the two-tier network (Figure 4b) are up to 65 dB better in the FAP areas than in the macro-only network; and up to 10 dB better at 30 m indoors and outdoors around each FAP (impact is visible as well in the neighbor building). Figure 4c illustrates the SINR levels for *FAP subscribers*. Users inside the FAP areas are assumed to be *FAP subscribers*. Thus, as for *corporate FAP subscribers*, SINR levels in the FAP areas are up to 65 dB better than in the macro-only network. On the other hand, users outside the FAP areas are assumed to be *non-subscribers*, thus the SINR levels are up to 17 dB worse within 30 m around the active FAP than in the macro-only network. Finally, Figure 4d shows the SINR map for *non-subscribers* still in presence of closed-access FAPs; the SINR levels are up to 40 dB worse in the active FAP area than in the macro-only network.

Table 2 Scenario 1 description for local impact analysis of a FAP deployment on network coverage

Category	Parameter values
Propagation modeling	Synthetic environment model
	Analytical propagation models
Traffic in macro layout	Traffic load: 50%
FAP deployment	Building size: 20 × 60 m^2; composed of 2 × 6 small areas of size 10 × 10 m^2
	Distance to the macro site: greater than ISD/3
	FAP density: 20%
Traffic in femto layout	Activation ratio: 50%
	Traffic load: 10%

Figure 6 shows the SINR maps at the first floor (i.e., the floor above the FAP deployment) from the same run. The SINR levels from the macro-only network range similar to ground floor since the network is interference limited (both signal and interference levels are higher than at ground floor). The SINR levels for *corporate FAP subscribers* in the two-tier network (Figure 6b) are better than in the macro-only network by up to 35 dB in the areas located just above the FAPs. Finally, Figure 6d shows the SINR map for *non-subscribers*. The SINR levels are lower than in the macro-only network by up to 27 dB in areas located above the active FAP.

Thus, FAPs have a large impact (either gain or degradation) on the SINR levels experienced by *FAP subscribers* and *non-subscribers*, not only at the same floor, but also at the upper floor and in neighbor buildings. The next section deals with the impact observed from the whole Monte Carlo process in terms of spectral efficiency distributions.

Spectral efficiency distributions analysis

The local impact of a FAP deployment is evaluated in terms of spectral efficiency distribution. The cumulative distribution functions (CDFs) from the macro-only network and the two-tier network are compared for the three different types of user (*FAP subscriber, corporate FAP subscriber,* and *non-subscriber*).

First, Figure 7 compares the spectral efficiency CDFs in the macro-only network and in the two-tier network for *FAP subscribers*, in both open- and closed-access modes. The macro-only network provides full service coverage but limited spectral efficiency (1.1 bps/Hz on average). The FAPs enable a tremendous improvement in the coverage quality since they provide the maximum spectral efficiency of the system (5.2 bps/Hz) in 90% of FAP areas in closed-access mode and in 95% in open-access mode. The difference comes from the fact that, in open-access mode, users can connect to FAPs in neighbor rooms if one of those FAPs becomes its best-server. Finally, active FAPs create dead zones (areas without service coverage due to strong interference from FAPs) for *non-subscribers* in their whole FAP areas (therefore there is no related curve in Figure 7).

Second, Figure 8 gives the impact of FAPs on the spectral efficiency CDFs at ground floor (FAP deployment floor) both for *non-subscribers* and *corporate FAP subscribers*, which is in line with observations made previously on SINR maps above. For *non-subscribers*, FAPs

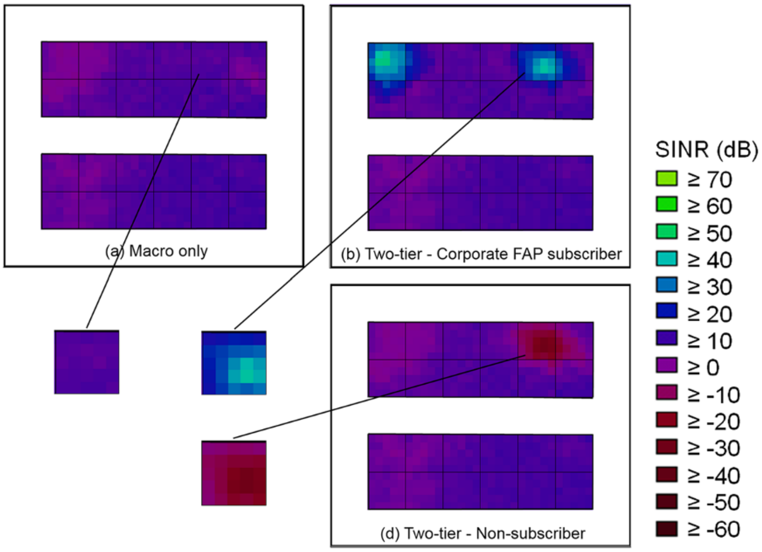

Figure 6 **Scenario 1—SINR maps at the first floor.**

create dead zones in 20% of ground floor and the average spectral efficiency slightly decreases, whereas for *corporate FAP subscribers* the average spectral efficiency increases by 1 bps/Hz and 25% of ground floor benefits from the maximum spectral efficiency (5.2 bps/Hz).

Figure 9 shows the impact of FAPs on the spectral efficiency CDFs at the first floor, i.e., the floor above the FAP deployment. The spectral efficiency CDF of the macro-only network is very close to the one at ground floor (see Figure 8). This is the direct result of similar SINR levels observed previously since the network is interference limited. For *non-subscribers*, FAPs create dead zones in 8.5% of the floor (compared to 20% at ground floor) but the average spectral efficiency is almost the same than in the macro-only network. For *corporate FAP subscribers*, the average spectral efficiency increases by only 0.4 bps/Hz but 10% of the first floor benefits from the maximum spectral efficiency (5.2 bps/Hz). Thus, the impact of FAPs deployed at a neighbor floor is much localized.

The impact of FAP properties and distance to the closest macro site is shown in Figures 10, 11, and 12. The reference scenario is described in Table 2.

First, Figure 10 illustrates the impact of distance to the macro site on the spectral efficiency predicted for *FAP subscribers* (i.e., subscribers located inside FAP areas). The benefit is lower for *FAP subscribers* located near the central macro site (short range case) than for the ones located far away (large range case), because the macro-to-FAP-user interference is higher, but the observed spectral efficiency is still very good. Conclusion is similar when considering 10 dBm FAP transmit power compared to 20 dBm.

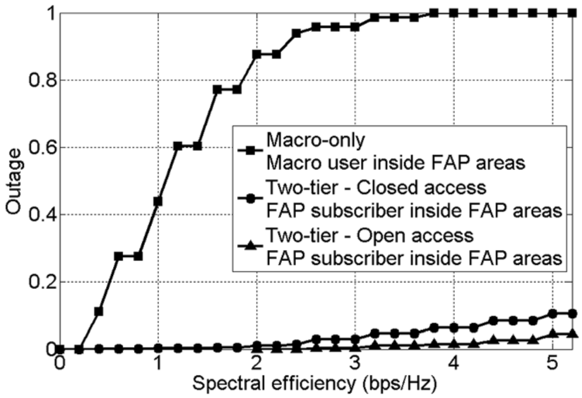

Figure 7 **Scenario 1—spectral efficiency CDFs of macro-only and two-tier networks in FAP areas.**

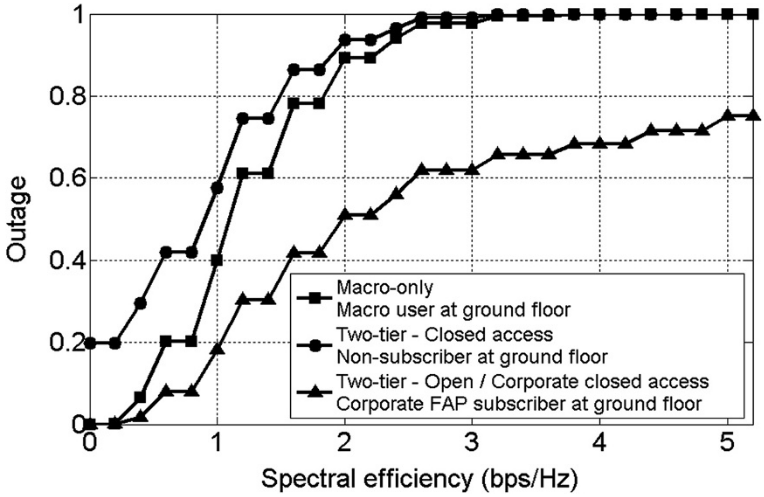

Figure 8 Scenario 1—spectral efficiency CDFs of macro-only and two-tier networks at ground floor.

Figure 11 shows the impact of several parameters for *non-subscribers* located at ground floor (deployment floor):

- Degradation nearby the macro site is similar in terms of average spectral efficiency than in reference scenario (0.3 bps/Hz worse on average, see green versus blue curves and black versus orange curves). However, the dead zones are smaller (10% versus 20%) since the useful signal level from the macro-BS is higher.
- Reducing the FAP transmit power from 20 to 10 dBm reduces the dead zones from 20 to 12% of ground floor.
- Increasing the FAP density from 20 to 50% increases the dead zones from 20 to 45% of ground floor.

Figure 12 shows a similar study for *corporate FAP subscribers*:

- Nearby the macro site (blue curve):
  - The minimum spectral efficiency is higher than in reference scenario thanks to greater macro-BS signal level in its best server area;
  - The maximum spectral efficiency (5.2 bps/Hz) is available in a smaller area than in reference scenario due to higher macro-to-femto interference level: 15% of the ground floor instead of 25%.
- Reducing the FAP transmit power from 20 to 10 dBm reduces the spectral efficiency by 0.7 bps/Hz on average (red curve).

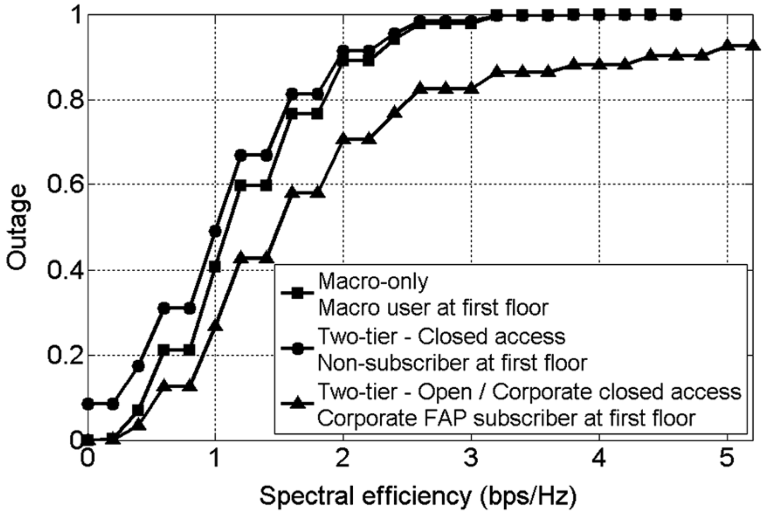

Figure 9 Scenario 1—spectral efficiency CDFs of macro-only and two-tier networks at first floor.

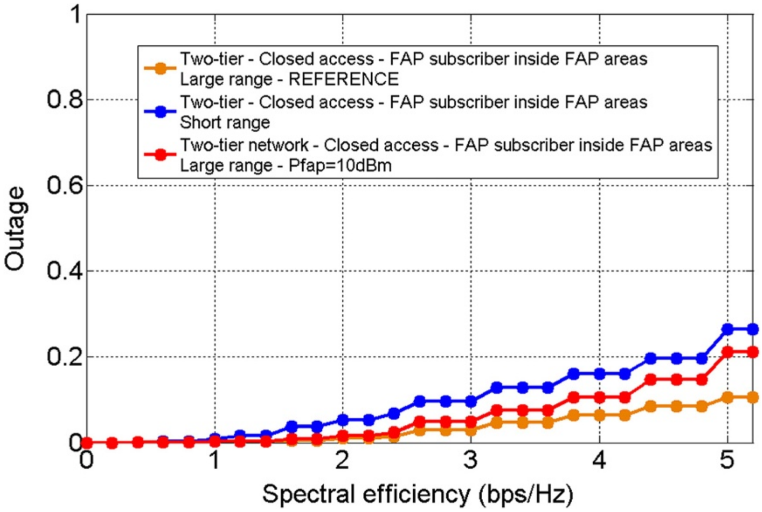

Figure 10 Scenario 1—impact of FAP properties on *FAP subscriber* spectral efficiency in FAP areas.

- Increasing the FAP density from 20 to 50% increases the spectral efficiency by 1 bps/Hz on average (purple curve).

Impact of a large-scale and dense corporate FAP deployment on macro coverage

Realistic and large-scale analyses are performed in real environments using a site-specific propagation model and high-resolution geographical map data. The objective is to evaluate in a realistic scenario the network coverage evolution after corporate FAPs have massively been deployed in urban macrocells, as illustrated in Figure 5. The scenario is based on a downtown area of a European large city. The parameters are given in Tables 1 and 3.

Figure 13 compares the spectral efficiency CDFs of indoor users. The impact for *non-subscribers* on the average spectral efficiency is very slight (<0.1 bps/Hz). However, the closed-access FAPs create dead zones in 15% of indoor areas. On the opposite, for *corporate FAP subscribers*, the two-tier network provides full service coverage and a spectral efficiency 1.5 bps/Hz better in 20% of indoor areas.

Figure 14 compares the spectral efficiency CDFs of outdoor users. The average spectral efficiencies are quite close in the three simulated cases. The local impact of FAPs is obviously lower than for indoor users but is still visible: closed-access FAPs create dead zones for *non-subscribers* in 3% of outdoor areas. On the opposite, for *corporate FAP subscribers*, the two-tier network provides

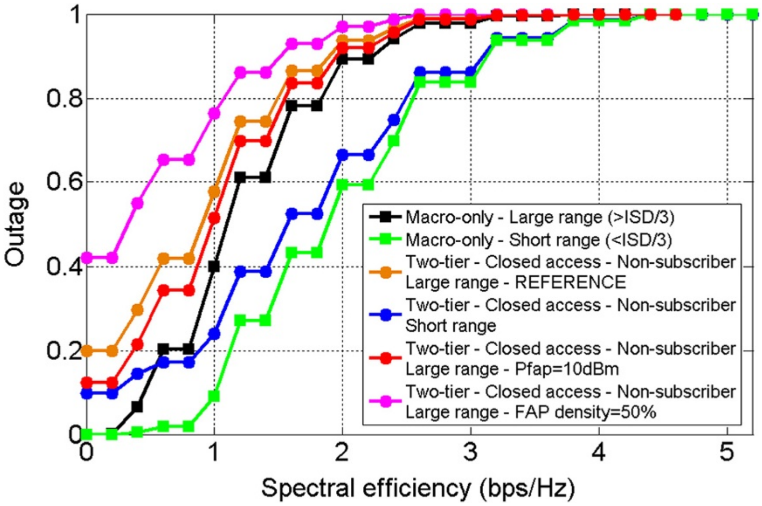

Figure 11 Scenario 1—impact of FAP properties on *non-subscriber* spectral efficiency at ground floor.

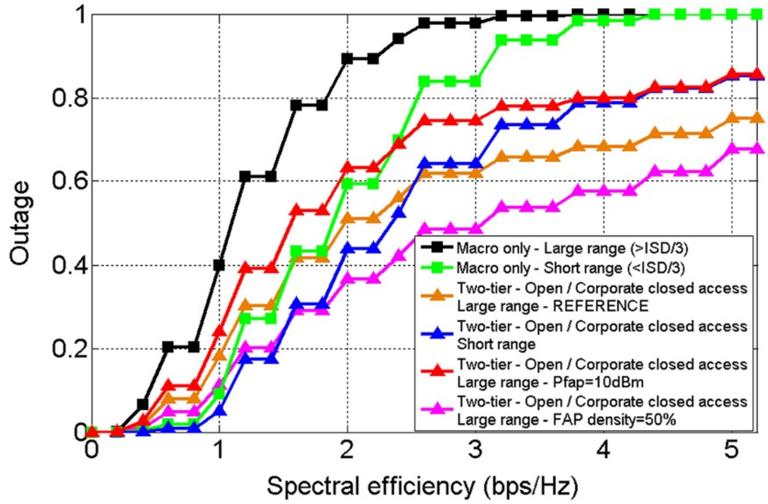

Figure 12 **Scenario 1—impact of FAP properties on *corporate FAP subscriber* efficiency at ground floor.**

full service coverage and a spectral efficiency 0.6 bps/Hz better in 20% of outdoor areas.

The evaluation of the impact of FAP deployments on the network coverage quality requires advanced tools and a thorough analysis. The average spectral efficiency does not provide enough information and thus location-specific CDFs are required to identify the locally strong impact (gain or degradation) of FAPs for indoor and outdoor users, as function of FAP access mode and user type.

Conclusion

This article introduces an original solution exploited to provide a 3D analysis of the impact of FAP deployments on the coverage quality in realistic scenarios. It offers two complementary approaches for two different applications:

- a synthetic model for detailed analysis of local impact of FAPs and realization of illustrative case studies (in FAP areas, at deployment floor, in building floors, etc.);
- a real model for large-scale two-tier network performance evaluation in realistic scenarios.

Table 3 Scenario 2 description for impact analysis of dense corporate FAP deployments in a macro network

Category	Parameter values
Propagation modeling	Real environment model
	Site-specific propagation model
Traffic in macro layout	Traffic load: 50%
FAP deployment	Corporate building ratio: 20%
	FAP density within corporate buildings: 20%
Traffic in femto layout	Activation ratio: 50%
	Traffic load: 10%

The novelty mainly lies into the integration (partly random) of the femtocell layout into a synthetic or real macro network and into the 3D aspect, as the coverage maps are calculated in streets and in different building floors. Furthermore, both open- and closed-FAP access modes and different user types (*FAP subscriber, non-subscriber*) are handled, enabling to evaluate in-depth different FAP deployment strategies.

A first study evaluates the local impact of a FAP deployment in one restricted urban corporate area in presence of existing macro coverage with the synthetic model. The results show that the macro-only network provides full service coverage but limited spectral efficiency (1.1 bps/Hz on average). A closed-access FAP deployment enables a tremendous improvement for *FAP subscribers* (up to 5.2 bps/Hz in 95% of 100 m^2 FAP areas) but creates dead zones in all FAP areas for *non-subscribers.* The coverage quality of the whole deployment floor (ground floor) is also tremendously impacted: *corporate FAP subscribers* benefit from the maximum spectral efficiency (5.2 bps/Hz) in 25% of the floor, whereas *non-subscribers* encounter dead zones in 20% of the floor. The impact of the ground floor deployment at the first floor is also significant: *corporate FAP subscribers* benefit from the maximum spectral efficiency (5.2 bps/Hz) in 10% of the floor, whereas *non-subscribers* encounter dead zones in 8.5% of the floor. These last results illustrate the relevance of the approach proposed in this article since a FAP deployment

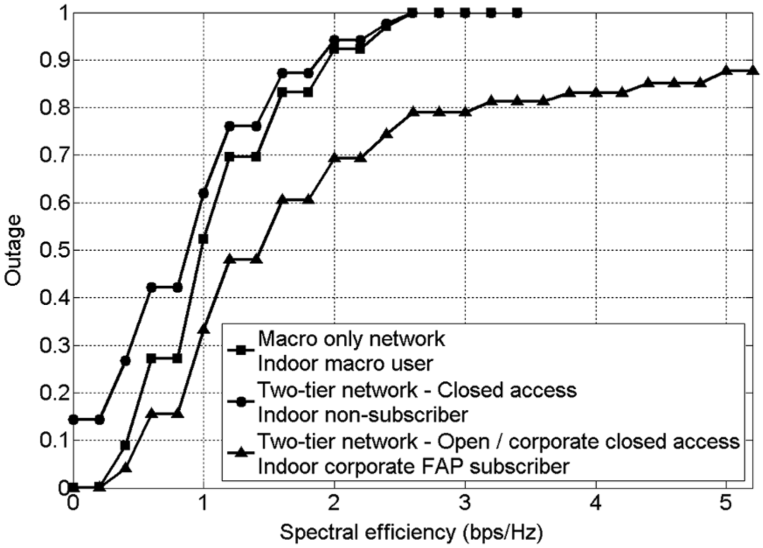

Figure 13 **Scenario 2—spectral efficiency CDFs of macro-only and two-tier networks indoors.**

has a strong local impact not only at deployment floor, but also in neighbor floors. Furthermore, the impact can be a large improvement or degradation of coverage quality according to the FAP access mode and to the user type. Besides, the FAP properties (transmit power, FAP density, etc.) and the distance to the macro site have a visible impact on interference levels and thus on coverage quality but the previous conclusions remain valid.

The second study evaluates the network coverage evolution after corporate FAPs have massively been deployed in urban macrocells. A real environment (high-resolution geographical map data) and a site-specific model are used to bring realistic spatial correlation and variability in pathloss predictions of a typical two-tier network with FAPs. The results show a moderate impact on the average spectral efficiencies. However, the evaluation of the impact of FAP deployments on the network coverage quality requires a thorough analysis. The average spectral efficiency does not provide enough information since FAPs have a strong impact locally. In this study, closed-access FAPs cause dead zones for *non-subscribers* in 15% of indoor areas leading to non-uniform service coverage, whereas FAPs increase the spectral efficiency of *corporate FAP subscriber* by at least 1.5 bps/Hz in 20% of indoor areas. These are critical

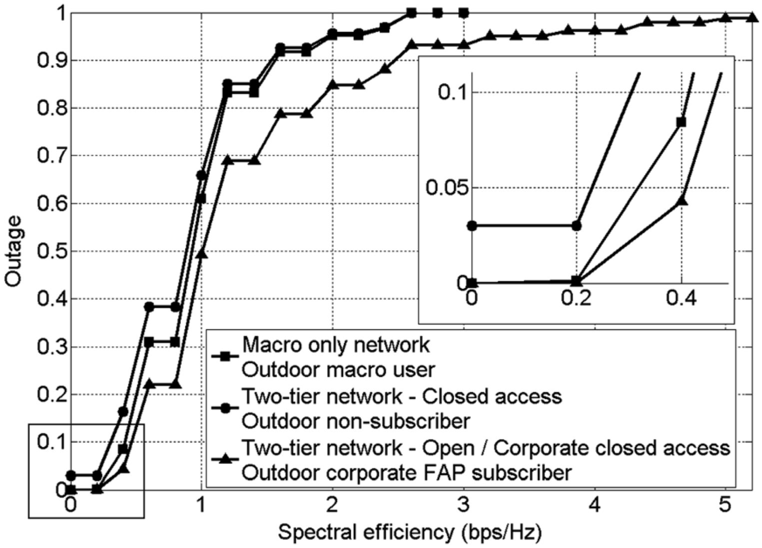

Figure 14 **Scenario 2—spectral efficiency CDFs of macro-only and two-tier networks outdoors.**

information for a mobile operator since the experience of its customers is much affected by the FAP deployment and by the selected access-mode.

Competing interests

The authors declare that they have no competing interests.

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References

1. Informa telecoms & media, Femtocell market status, issue 8, (2011). Available on website http://www.femtoforum.org
2. G. de la Roche, A. Valcarce, D. Lopez-Perez, J. Zhang, Access control mechanisms for femtocells. IEEE Commun. Mag. **48**(1), 33–39 (2010)
3. J.B. Vezin, L. Giupponi, A. Tyrrel, E. Mino, M. Brzozowy, A femtocell business model: the BeFEMTO view, in *2011 Conference Proceedings of Future Network and Mobile Summit (FUNEMS)*, ed. by (Varsaw, Poland, 2011), pp. 1–8
4. Femto Forum, *Interference management in UMTS femtocells* (2010)
5. Femto Forum, *Interference management in OFDMA femtocells* (2010)
6. H. Claussen, D. Calin, Macrocell offloading benefits in joint macro- and femtocell deployments, in *Proceedings of IEEE 20th Symposium on Personal* (Indoor and Mobile Radio Communications (PIMRC), Tokyo, Japan, 2009), pp. 350–354
7. Z. Bharucha, A. Saul, G. Auer, H. Haas, Dynamic resource partitioning for downlink femto-to-macro-cell interference avoidance. EURASIP J. Wirel. Commun. Netw **2010**(Article ID 143413), 1–12 (2010)
8. A. Barbieri, A. Damnjanovic, T. Ji, J. Montojo, Y. Wei, D. Malladi, O. Song, G. Horn, LTE femtocells: system design and performance analysis, in *Vehicular Technology Conference (VTC Spring)*, ed. by (2011 IEEE 73rd, 2011), pp. 1–5
9. A. Valcarce, L.-P. David, G. De La Roche, J. Zhang, Limited access to OFDMA femtocells, in *Proceedings of IEEE 20th Symposium on Personal* (Indoor and Mobile Radio Communications (PIMRC), Tokyo, Japan, 2009), pp. 1–5
10. O. Namgeol, H. Sang-wook, K. Hoon, System capacity and coverage analysis of femtocell networks, in *Proceedings of IEEE Wireless Commun. Network Conf. (WCNC)* (Sydney, Australia, 2010), pp. 1245–1249
11. Y. Corre, J. Stephan, Y. Lostanlen, Indoor-to-outdoor path-loss models for femtocell predictions, in *Proceedings of IEEE 22nd Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)* (Toronto, Canada, 2011), pp. 824–828
12. ICT-FREEDOM project, http://www.ict-freedom.eu
13. International Telecommunication Union, *ITU-R Recommendation P.1411-5, Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz* (Electronic publication, Geneva, 2009). http://www.itu.int/rec/R-REC-P.1411-5-200910-S/en
14. E. Damosso, L.M. Correia, *COST Action 231, Digital mobile radio towards future generation systems: Final report* (European Commission, 1999), p. 167
15. SIRADEL, http://www.siradel.com
16. Y. Corre, Y. Lostanlen, Three-dimensional urban EM wave propagation model for radio network planning and optimization over large areas. IEEE Trans. Veh. Technol **58**, 3112–3123 (2009)
17. C. Mehlführer, M. Wrulich, J.C. Ikuno, D. Bosanska, M. Rupp, Simulating the long-term evolution physical layer, in *Proceedings of 17th European Signal Processing Conference (EUSIPCO 2009)* (Glasgow, Scotland, 2009), pp. 1471–1478

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