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Additional Information

Access Control Mechanisms for Femtocells

Guillaume de la Roche, Alvaro Valcarce, David López-Pérez, and Jie Zhang, University of Bedfordshire

ABSTRACT

Femtocells are a solution that helps to reduce the capital and operational expenditure of a mobile network while enhancing system coverage and capacity. However, the avoidance of interference is still an issue that needs to be addressed to successfully deploy a femtocell tier over existing macrocell networks. Moreover, interference is strongly dependent on the type of access control, which decides if a given user can or cannot connect to the femtocell. In this article the existing access methods for femtocells together with their benefits and drawbacks are explained. A description of the business model and technical impact of access methods in femto/macro networks is also provided. Finally, the need for hybrid access methods and several models are presented.

INTRODUCTION

To remain competitive in the wireless communication market, vendors and operators need to make the reduction of both network cost and complexity a priority in future deployments of cellular systems. Moreover, the growth of indoor traffic forces network operators to compete with existing indoor coverage solutions, such as WiFi and Distributed Antenna System (DAS) to maintain their revenues.

Since 2/3 of voice and 90 percent of data traffic occurs indoors [1], and because macrocells are not very efficient when delivering indoor coverage due to high penetration losses, providing such coverage has become a challenge for operators. That is why the use of femtocell access points (FAPs) seems a promising approach for coping with this coverage problem. An FAP is a low-cost low-power cellular base station deployed by the end customer. It is expected that femtocells will enhance indoor coverage, and also deliver high bandwidths, offer new services, and offload traffic from existing networks [2].

Nevertheless, these benefits are not easy to accomplish. There are still several challenges vendors and operators must face in order to deploy a large number of FAPs on top of the existing macrocells. Electromagnetic interference remains among the major problems in two-tier networks, capable of hindering the above mentioned benefits and degrading the entire network's performance [3].

In two-tier networks, interference is classified as follows:

- *Cross-tier* interference is caused by an element of the femtocell tier to the macrocell tier and vice versa.
- *Co-tier* interference occurs between elements of the same tier, for example, between neighboring femtocells.

The impact of interference depends on the techniques used for allocating the spectral resources to the macrocell and femtocell tiers, as well as on the method used to access the femtocells.

In an orthogonal deployment of macrocells and femtocells, where separate carriers are assigned to each tier, cross-tier interference is entirely removed. However, this happens at the expense of decreasing the spectral efficiency of the network.

Contrarily, co-channel deployments, where the carriers are shared between both tiers, can result in higher spectral efficiency throughout the use of self-organization techniques. In this case and to fight interference, intelligent allocation of the power, frequency, and time resources of the FAP must be performed based on an accurate sensing of the radio environment, as well as optimal tuning of its parameters. This way, cross-tier interference can be efficiently mitigated.

Moreover, the selection of an access control mechanism for femtocells has dramatic effects on the performance of the overall network, mainly due to its role in the definition of interference. Different approaches have been proposed (Fig. 1):

- *Closed access*: Only a subset of users, defined by the femtocell owner, can connect to the femtocell. This model is referred to as closed subscriber group (CSG) by the Third Generation Partnership Project (3GPP) [4].
- *Open access*: All customers of the operator have the right to make use of any femtocell.
- *Hybrid access*: A limited amount of the femtocell resources are available to all users, while the rest are operated in a CSG manner.

When the access method blocks the use of femtocell resources to a subset of the users

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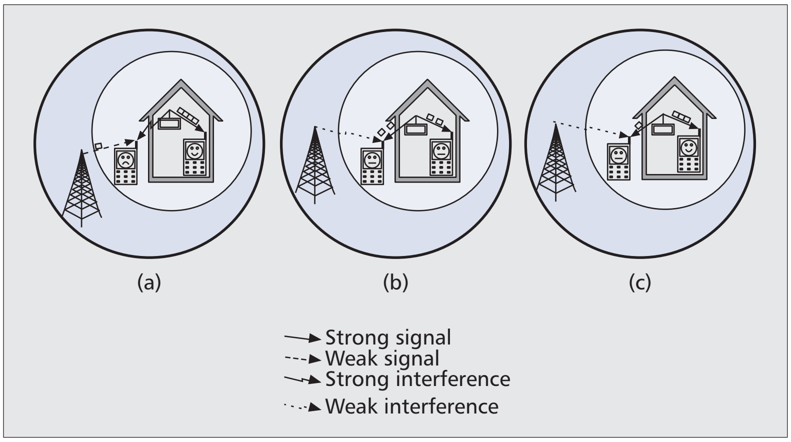

Figure 1. *Access methods: a) closed subscribers group (CSG); b) open access; c) hybrid access.*

within its coverage area, a new set of interfering signals is implicitly defined in such area. Hence, the deployment of CSG femtocells makes the problem of interference mitigation even more complex. Contrarily, the deployment of open FAPs would solve this issue, but bring security and sharing concerns to the customer. Furthermore, when users move across areas with large numbers of open FAPs, the number of handovers and thus the signaling in the network increases. Finally, hybrid access techniques can be seen as a trade-off between open and closed approaches. However, the number of shared resources must be carefully tuned to avoid a large impact on the quality of service of the femtocell customers.

Access control mechanisms play an important role in mitigating cross-tier interference and handover attempts, which is why they have to be carefully chosen depending on the customer profile and the scenario under consideration. The goal of this article is to provide an overview of the existing access methods [5] to femtocells (i.e., open, closed, and hybrid), as well as to describe in detail the benefits and drawbacks of each of them. Furthermore, the business case, scenarios, and technical challenges of different access mechanisms along with some potential solutions are presented. In addition, system-level performance analyses of these methods in terms of network outages, throughput, and handover are provided.

ACCESS METHODS

In order to describe the access control procedures to femtocells in a two-tier network, users need to be classified according to their femtocell connectivity rights. In this context:

- A *subscriber* of a femtocell is a user registered in it. Subscribers are thus the rightful users of the femtocell, and they are usually mobile terminals that belong to the femtocell owner, their family, or their friends.
- A *nonsubscriber* is a user not registered in the femtocell.

In the following, the access control procedures to femtocells are described in terms of this classification.

CLOSED ACCESS

In closed access, only the femtocell subscribers are allowed to connect to the femtocells.

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

Co-tier interference also comes up between neighboring femtocells in dense deployments. In many cases users will install their femtocells in random positions within their homes (e.g., close to a room of a neighbor or close to a window). In this case subscribers will sometimes be severely jammed by neighboring femtocells, and thus unable to connect.

Therefore, solutions are required to reduce both cross-tier and co-tier interference, allowing the deployment of a large number of femtocells within the existing networks. Interference cancellation and avoidance techniques for femtocell networks are hence currently an important research topic.

In order to guarantee femtocell connectivity and mitigate interference, the power radiated by the FAP must be tuned to ensure sufficient coverage to femtocell subscribers and minimize leakage of power outside the premises. This can be done by self-optimizing the femtocell radiated power in an approach similar to [6], where each femtocell sets its power to a value that on average is equal to the received signal strength from the closest macrocell in a target femtocell radius.

Another solution to mitigate the interference problem is the use of sector antennas in the FAPs, which has been proposed in [7] to minimize the overlapping of coverage areas. Furthermore, the use of several radiating elements to perform beamforming and adapting the coverage area of the femtocell to the shape of the household have also been suggested in [8].

Moreover, orthogonal frequency-division multiple access (OFDMA) femtocells have the advantage of allowing the allocation of orthogonal frequency/time resources to users. Thus, interference avoidance can be handled through not only power or antenna management, but also subchannel and time slot allocation. Nevertheless, the success of these interference mitigation techniques relies on the ability of femtocells to monitor the environment and optimally assign their resources based on the obtained information [9].

Scenarios — The first closed access femtocell deployments occurred in homes where coverage from macrocells was poor, but broadband connectivity sufficiently deployed. For example, in the middle of North America, Sprint has deployed femtocells since the end of 2008. Nevertheless, this solution is only aimed at the home market, where in this case interference is not an important issue due to the low population density and the large distances to macrocells. However, recent deployments have also been proposed in Europe, where femtocells are aimed at homes in cities and where interference could be a challenge. This is the case, for example, in the United Kingdom, where home femtocells started to be commercialized by Vodafone in July 2009. As shown in Fig. 2, in the future femtocells will also be available to enterprises, and it is thus expected that closed access femtocells could be deployed in small to medium-sized enterprises (SMEs)/offices, where a limited number of users would be authorized to access them.

Business Model Issues — According to recent surveys [1], closed access is the preferred access method of customers for home femtocells. The main reason is that most customers would only accept having a femtocell at home if they had full control over the list of authorized users.

Moreover, femtocells must allow all types of users to perform emergency calls by law. This implies that some resources have to be released by each FAP in order to ensure that nonsubscribers are also able to perform emergency calls.

Concerning the pricing of femtocell solutions, different approaches have been proposed. The first option is that operators provide the FAP for free or sell it at a fixed price, in order to improve only their radio coverage. But to increase their revenue and compete with the landline market, it is expected that operators will also try to offer special rates (or free calls) to femtocell subscribers. Moreover, to attract new customers, manufacturers and operators are currently putting a lot of effort into developing new *killer* applications for femtocells.

OPEN ACCESS

In open access, all users (subscribers and nonsubscribers) are allowed to connect. There is thus no distinction between these two groups, and they are just referred to here as users.

Technical Challenges and Solutions — The use of open FAPs at home would reduce the interference problems caused by CSG FAPs. Indeed, all passing users would be authorized to connect to any femtocell, thus reducing the negative impact of the femtocell tier on the macrocell network. In this case the users are always connected to the strongest server (either macro or femto), avoiding cross-tier interference. As a result, the overall throughput of the network increases (Fig. 3).

Furthermore, open access FAPs allow different types of deployments. Inside homes, this type of FAP will be deployed in random locations, self-organization being a good solution to minimize the negative impact of femtocells on other cells. On the other hand, when deployments are done by an operator, interference can be mitigated throughout network planning and optimization. The location, power, and frequencies assigned to each femtocell can in this case be planned in advance.

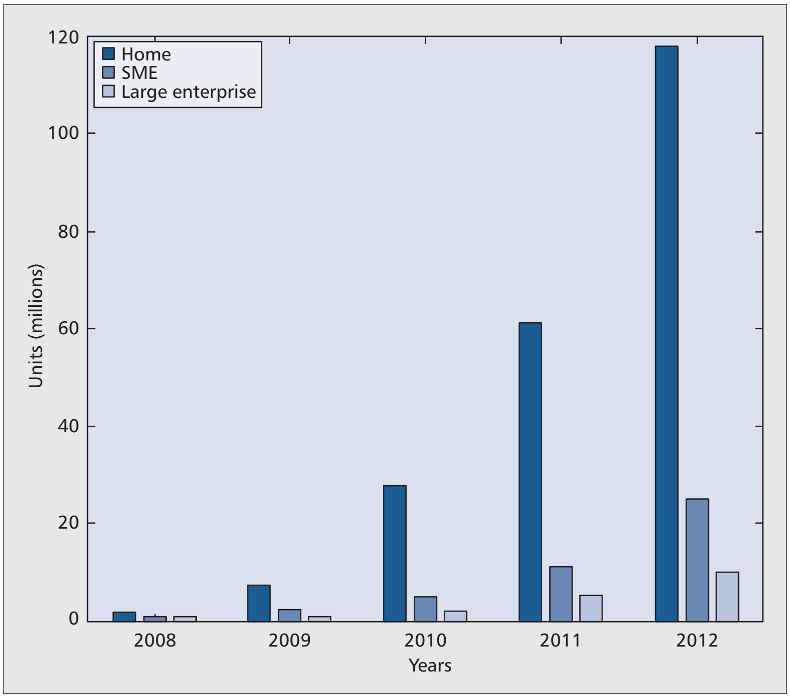

Figure 2. *Forecast: number of units (data extracted from ABI Research [1]).*

Nevertheless, open access has some drawbacks as well. It reduces the performance for the femtocell owner due to the sharing of the femtocell resources with nonsubscribers. Moreover, open access substantially increases the amount of handovers between cells due to the movement of outdoor users. A user moving in a residential area will hand over from one femtocell to another or to the umbrella macrocell (Table 2). This will have a negative impact on the operator because the signaling in the network increases as well as the probability of the call being dropped due to failure in the handover process.

Furthermore, the chances for handover failure increase if the femtocell neighbor list is not properly configured and updated. Regardless of this, different solutions have been proposed in which a centric sensing of the radio channel is used as a means to obtain parameters about the surrounding environment and update the femtocell neighbor list [10].

Moreover, current base stations store only a few neighbor relationships in such a list. For example, the neighboring list in UMTS macrocells has been limited to 32 positions to speed up the user measurement and cell updating procedures. However, this number will be insufficient in large open access femtocell deployments, where the relationships between femtocells (more likely to be turned on and off) must be handled in a different way than between macrocells and femtocells.

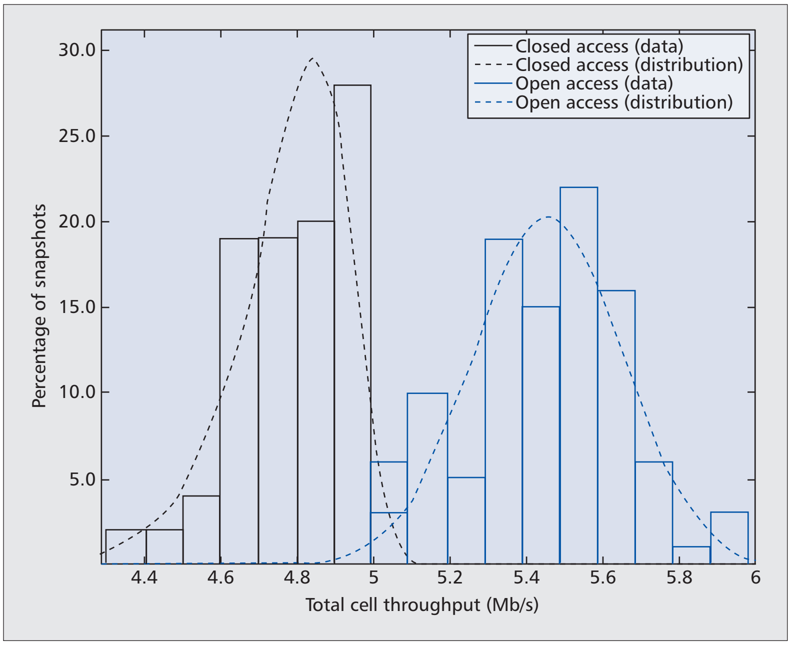

Figure 3. *Total downlink network throughput in a residential (200 × 100 m) area covered by 22 OFDMA femtocells and 1 macrocell (10 MHz bandwidth). Each house hosting a femtocell contains two indoor users demanding 128 kb/s each. Furthermore, 10 macro users were located outdoors demanding 64 kb/s each. The system-level simulation is based on Monte Carlo snapshots.*

In addition, if femtocells are massively deployed and given that the number of cell identities is limited (e.g., UMTS supports 512 cell IDs), there would not be enough cell IDs to allocate to all femtocells within the coverage area of a macrocell. Therefore, the reuse of cell IDs within the coverage of a single macrocell would be necessary, and collision and/or confusion between some of them would be unavoidable.

Hence, before open FAPs are widely deployed, research is required in order to support new algorithms to handle more neighbors and their different natures in a fast manner. New approaches are also needed to dynamically select the cell ID of the femtocells, while minimizing confusion and collision.

Scenarios — As explained before, the commercialization of open access femtocells is not currently preferred by home customers. However, as shown in Fig. 3, open access reduces the negative impact of femtocells on macrocells. That is why in the future, when most of the technical challenges are solved, operators may try to promote open access femtocells for the home market. Another major market for femtocells resides in industry, SMEs or larger companies. In this scenario femtocells are deployed by either the operator or self-installed by the end customer, taking advantage of the low price of FAPs compared to other solutions like picocells, indoor repeaters, or distributed indoor systems. Furthermore, if femtocells are self-configurable, such deployments are interesting for the operator since maintenance is minimized. In a similar manner femtocells can, following careful planning, be deployed in public areas such as airports, parks, and train stations in order to improve coverage and user experience.

Business Model Issues — In the first instance commercialization of open access femtocells is mainly targeted at the enterprise market. In this business model emergency calls are not an issue because all passing users are allowed to make use of the FAPs.

Depending on the scenario, it is not always clear who should cover the costs of the femtocells and their maintenance. In many situations the FAP owner, knowing that its neighbors will use its femtocell, will not be keen on paying the same price as if the femtocell was closed. Moreover, it is to be noticed that open femtocells reduce the load of the macrocell network, and are thus advantageous for operators, who can either support new customers or save money in macrocell maintenance (e.g., power). Therefore, it is expected that these femtocells will be partially or fully paid for and maintained by network operator.

COMPARISON AND NEED FOR HYBRID APPROACHES

In Table 1 the main features of both CSG and open access are summarized. To analyze the overall performance of these access methods, experimental system-level simulations have been performed. The test environment is a residential area where a large deployment of femtocells and a macrocell have been considered. The simulation is based on a deterministic radio coverage prediction tool calibrated with measurements [11], and a Monte Carlo snapshot-based WiMAX system-level simulator. Further details about this tool and the parameters of this experimental evaluation can be found in [12]. This experiment verifies that the overall network throughput of open access outperforms that of closed access (Fig. 3).

In Table 2 the performance of CSG and open access is compared in terms of user outages and handover signaling. In this case a dynamic system-level simulation is used in order to evaluate the performance of these two access methods, while considering the mobility features of outdoor customers. On one hand, it can be seen that in CSG femtocells the number of outages is large due to cross-tier interference. In this case a user is considered to be in outage (dropped call) when it is not able to transmit for a given period of time. This period of time has been set to 200 ms as it is recommended for voice over IP (VoIP) services. On the other hand, in open access there are several handover attempts, which cause outages due to handover failure. In this case a handover attempt is made every time the received signal strength of the pilot signal of a neighboring cell is larger than that of the serving cell. Note that according to [6], there is a 2 percent probability that a handover results in a dropped call (outage). Even so, in this case the number of outages is notably lower than in closed access. Further information about this dynamic simulator (channel modeling, interference modeling, throughput calculation, etc.) can be found in [9].

Finally, let us note again that open FAPs are unlikely to be deployed in homes, due to the preferences shown by customers, who are more attracted by the CSG access model. Hence, a third type of access method, midway between CSG and open access, is currently being researched (Fig. 1c).

Closed access femtocells	Open access femtocells
Higher interference	More handovers
Lower network throughput	Higher network throughput
Serves only indoor users	Increased outdoor capacity
Home market	SMEs, hotspots
Easier billing	Security needs

Table 1. *Closed vs. open access.*

HYBRID APPROACHES

Access control mechanisms have a direct effect on interference, and their features must hence be carefully analyzed. As seen in the previous section, all access methods suffer from advantages and drawbacks. In order to overcome those drawbacks, intermediate approaches are currently under scrutiny.

Hybrid access methods reach a compromise between the impact on the performance of subscribers and the level of access granted to nonsubscribers. Therefore, the sharing of femtocell resources between subscribers and nonsubscribers needs to be finely tuned. Otherwise, subscribers might feel that they are paying for a service that is to be exploited by others. The impact on subscribers must thus be minimized in terms of performance or via economic advantages (e.g., reduced costs). In this section particular cases of hybrid access methods for several technologies are depicted.

CODE-DIVISION MULTIPLE ACCESS

The performance of adaptive access to high-speed downlink packet access (HSDPA) femtocells was analyzed in [13]. This method consists of allowing a limited number of nonsubscribers to access the femtocell, this number being adapted depending on factors such as the traffic load at a given location and time.

This work showed that allowing nonsubscribers into the femtocell reduces the amount of nonsubscribers in outage. However, it was also shown that several nonsubscribers must be allowed into the femtocell in order to have less outage than if there were no femtocells. Furthermore, the admission of only a few nonsubscribers into the femtocell halves the throughput achieved by subscribers, which decreases further as more nonsubscribers are allowed access to the femtocells.

The reduction in the performance of subscribers stems from the intrinsic nature of the underlying technology. In code-division multiple access (CDMA) systems, transmissions from other users are seen as interference by the users already in the network. In this case, when a nonsubscriber is granted access to the femtocell, the noise rise deteriorates the instantaneous throughput of subscribers. Moreover, this scheme treats allowed nonsubscribers and subscribers equally (i.e., no data rate restrictions are imposed). Therefore, the incorporation of nonsubscribers degrades the performance of connected subscribers in an uncontrolled way.

In [14] it was further shown that traffic distribution also affects the performance of hybrid methods. For instance, hybrid approaches that allow access to many nonsubscribers can significantly improve the uplink packet success rate, although not as much in the downlink case. This work showed that uplink performance is in general more sensitive than the downlink to the type of access method.

OFDMA

In contrast to CDMA-based femtocells, OFDMA systems offer two degrees of freedom for the purpose of resource allocation (frequency and time), hence providing higher flexibility in the management of the resources nonsubscribers can use. Furthermore, since OFDMA resources (time slots and frequency subcarriers) are orthogonal, interference can also be better controlled in the neighborhood of the femtocell. Thus, users unable to connect to the macrocell because of lack of coverage or interference could still use a fraction of the femtocell resources.

The hybrid access method in OFDMA femtocell networks consists of managing the sharing of the OFDMA resources (frequency and time) between subscribers and nonsubscribers. Therefore and first of all, these resources have to be defined. In OFDMA systems *subchannels* contain a series of subcarriers, which can be adjacent or pseudo randomly distributed across the spectrum in order to exploit either multi-user or frequency diversity. A nonsubscriber allowed access to a given subchannel can use it, for instance, during the whole transmission frame. However, if the network operator owns only a little bandwidth for its femtocells, one subchannel might seem a large resource to be shared. In such situations it is necessary to increase the granularity of the resource allocation, subdividing subchannels over the time domain (OFDM symbols). In general, it can be said that the smaller the resource, the better the approximation to the solicited throughput of a nonsubscriber.

Since the amount of resources to share N_r is limited, different sharing strategies can be considered to define the hybrid access algorithm. First, it is necessary to dimension the scheduling method for nonsubscribers, which is not necessarily the same one used for subscribers. A simple approach could be to serve incoming nonsubscribers following a first in first out (FIFO) policy until all N_r resources have been assigned, rejecting further nonsubscribers. On the other hand, a round-robin procedure would be a more appropriate solution for femtocell deployments in public spaces (e.g., supermarkets), because it guarantees that all nonsubscribers will be served sooner or later. Furthermore, preferential users can be configured as subscribers (e.g., members of staff) if necessary, thus ensuring that they have preferential access.

Number of femtocells	25		36		49		64	
Access method	**Closed**	**Open**	**Closed**	**Open**	**Closed**	**Open**	**Closed**	**Open**
HO attempts in the network over 1 hour	—	342	—	480	—	680	—	887
Average hand IN attempts per femtocell over 1 hour	—	6.84	—	6.67	—	6.94	—	6.92
Average hand IN attempts per macrocell over 1 hour	—	171	—	240	—	340	—	444
Outages in the network over 1 hour	69	0	81	8	120	15	164	22
Average nonsubscribers tier throughput (Mb/s) over 1 hour	5.339	5.604	5.409	5.740	5.340	5.604	5.002	5.720
Average subscribers tier throughput (Mb/s) over 1 hour	51.228	52.081	69.545	71.342	51.228	52.081	124.230	130.445

Handover, outage, and throughput analysis in a residential area (300 × 300 m) covered by several femtocells and one macrocell, using 10 MHz bandwidth.
Each house hosting a femtocell contains four indoor users demanding one OFDMA subchannel each.
Furthermore, eight macro users were located outdoors and demanding one OFDMA subchannel each.
The system-level simulation is dynamic, and the outdoor users move throughout the scenario according to a pedestrian model.
Note that a hand IN toward a given cell *A* is performed when a communication is handed over from another cell *X* to cell *A*.

Table 2. *Performance comparison (1 hour simulation).*

Another solution, more suitable for residential femtocells, would be to use an approach that grants resources first to those users that request real-time traffic or lower data rates. This way, the impact on femtocell subscribers is kept low.

Another strategy that can be used is to have N_r adjusted online or even varying between geographical locations:

- If N_r remains *static*, the access mechanism is easier to implement, but the femtocell can suffer from lower spectral efficiency because it will not be able to cope with the changing behavior of the traffic. This approach is simple and suitable for scenarios with constant traffic demands (sensors, indoor location devices, etc.).
- If N_r varies *dynamically*, the spectral efficiency is enhanced. For example, more resources could be shared (N_r high) at noon in residential scenarios when femtocell subscribers are not in the premises and the streets are crowded. This way, the impact on femtocell subscribers is minimized when they are at home, and the service to nonsubscribers is improved in peak hours.

Finally, regarding the coexistence of different types of users, the access of nonsubscribers to the femtocell can be:

- *Shared* with subscribers, if all resources can be used by subscribers, but N_r are liberated and transferred to nonsubscribers when they arrive. This approach is flexible because it maximizes the throughput of femtocell subscribers when no nonsubscribers are present.
- *Restricted* to nonsubscribers, with N_r resources permanently booked in the femtocell for the use of nonsubscribers, regardless of whether they are active or not. This approach guarantees that subscribers do not perceive variations in their QoS due to incoming nonsubscriber connections. However, the spectral efficiency will be reduced because the reserved resources might remain unused most of the time. Nonetheless, emergency services might require the permanent availability of a small number of resources and thus a restricted approach.

To illustrate the effect of limiting the amount N_r of shared OFDMA resources, Fig. 4 shows some simulated average throughput predictions. This simulation is based on a Monte Carlo snapshot-based system-level simulation. Further details about the simulation and key parameters can be found in [15]. In this case the frequency band is divided into eight subchannels, of which N_r are shared among existing nonsubscribers. Results for different N_r values are displayed in the figure. It can be seen that reducing the amount of shared resources minimizes the impact on femtocell subscribers, thus exploiting the same features as a closed access method. Furthermore, it is also shown that sharing a small amount of resources ($N_r = 1$) is enough to dramatically reduce the probability of outage to nonsubscribers, just as with open access, but limiting the impact to the femtocell owner. It is also clear that larger values of N_r do not improve the outage probability of nonsubscribers, although their data rate is increased. Eventually, it is up to the operator to balance this parameter depending on the type of service they want to offer.

CONCLUSION

In this article different mechanisms of access to femtocells have been introduced. Both closed and open access models suffer disadvantages, the main ones being lower network performance due to cross-tier interference for closed access, and fewer customers' acceptance for open access, as well as a large number of handovers. Hence, hybrid strategies have been described, and models for CDMA and OFDMA have been detailed.

Unlike open and closed, where the access mode is clearly defined, hybrid access offers a full range of algorithms that can be defined in order to control who accesses the femtocell and how the connection is configured. Such an approach brings together the best of both worlds (closed and open access). Therefore, research is still needed to find hybrid access approaches well adapted to the different deployment scenarios.

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BIOGRAPHIES

GUILLAUME DE LA ROCHE (guillaume.delaroche@beds.ac.uk) has been working as a research fellow at the Centre for Wireless Network Design (CWiND), United Kingdom, since 2007. From 2001 to 2002 he was a research engineer at Infineon, Munich, Germany. From 2003 to 2004 he worked in a small French company where he deployed WiFi networks. From 2004 to 2007 he was with the CITI Laboratory at the National Institute of Applied Sciences (INSA), France. He holds a Dipl-Ing from CPE Lyon, France, and M.Sc. (2003) and Ph.D. (2007) degrees in wireless communications from INSA Lyon. He is a co-author of the book *Femtocells: Technologies and Deployment* (Wiley, 2010).

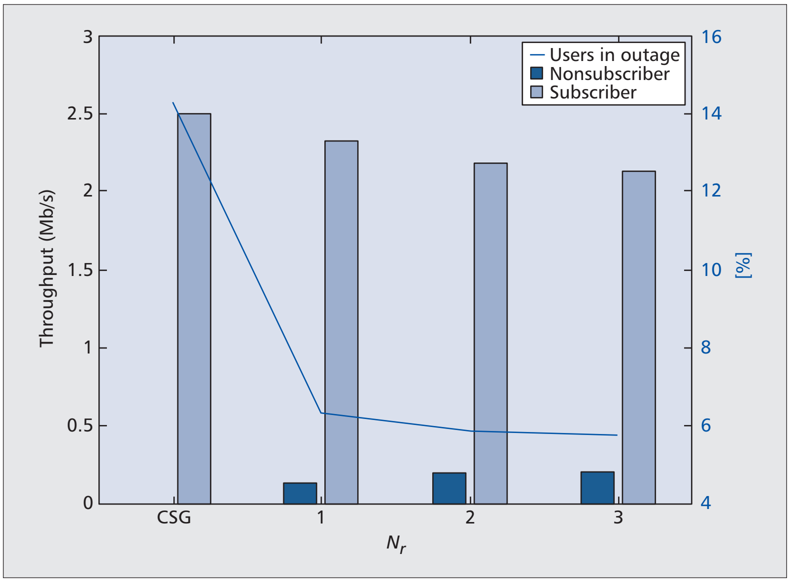

Figure 4. *Average throughput per user in a small residential scenario where 30 percent of the houses contains an OFDMA femtocell with 3 subscribers that request an intense data service. There are also 5 outdoor non-subscribers requesting a throughput between 80 and 450 kb/s for video service. The system-level simulation is based on Montecarlo snapshots.*

ALVARO VALCARCE obtained his M.Eng. in telecommunications engineering from the University of Vigo, Spain, in 2006. Then he was with the WiSAAR consortium in Saarbrücken, Germany, performing WiMAX trials and measurements data analysis. He joined CWiND at the University of Bedfordshire in 2007 with the support of a Marie Curie Fellowship. During 2008 he worked on the feasibility study of WiMAX-based femtocells for indoor coverage. His Ph.D. belongs to the FP6 RANPLAN-HEC project, which studies the indoor-to-outdoor wireless channel and its applicability to network planning and optimization.

DAVID LOPEZ-PÉREZ received his Bachelor and Master degrees in telecommunication from Miguel Hernandez University, Elche, Spain, in 2003 and 2006, respectively. He joined Vodafone Spain in 2005, working in the Radio Frequency Department in the area of network planning and optimization. He took up a research scholarship at the Cork Institute of Technology, Ireland, in 2006, where he researched indoor positioning systems and sensor networks. Nowadays, he is a Ph.D. Marie Curie Fellow at CWiND. He is involved in different FP6 and FP7 European projects, as well as EPSRC. His research interest is in two-tier networks, OFDMA, self-organization, and interference avoidance.

JIE ZHANG is a professor in the Department of Computer Science and Technology, University of Bedfordshire. He received his Ph.D. degree from East China University of Science and Technology in 1995. From 1997 to 2001 he was a research fellow with University College London, Imperial College London and Oxford University. He is the founding director of CWiND, one of the largest and leading research groups in 3G/4G radio access network planning and optimization in Europe. Since 2003, as principal investigator, he has been awarded 17 projects worth over US$6.0 million (his share) by the EPSRC, the European Commission (FP6/FP7), and the Nuffield Foundation. He is also lead author of the book *Femtocells: Technologies and Deployment* (Wiley, 2010).