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0. Executive Summary

In this report (D2.2), firstly, interference scenarios such as femtocell⇔femtocell and femtocell⇔macrocell in two-tier femto/macro networks will be analysed. Secondly, the performance degradations due to co-channel femtocell deployment in two-tier femto/macro networks will be demonstrated through system level simulation. Thirdly, the impact of different access control methods such as closed subscriber group (also called private access), open and hybrid access methods in terms of interference will be investigated. Finally, interference mitigation mechanisms in OFDMA based femtocells (e.g., WiMAX and LTE femtocells) will be proposed and their performances will be presented.

1 Introduction to femtocells

What is a femtocell?

Femtocells, also known as “**home base station**”, are cellular network access points that connect standard mobile devices to a mobile operator’s network using residential Digital Subscriber Line (DSL), cable broadband connections, optical fibre or future wireless last-mile access technologies. Hence, **a femtocell network = fixed network + cellular access points.**

What is included in a femtocell access point?

The femtocell unit incorporates the functionality of a typical base station (Node-B in UMTS). A femtocell unit looks like a WiFi access point, see Figure 1. However, it also contains RNC (Radio Network Controller; in the case of GSM, BSC) and all the core network elements. Thus, it does not require a cellular core network, requiring only a data connection to the DSL or cable to the Internet, through which it is then connected to the mobile operator’s core network, see Figure 2.

In this report, we use femtocell access point (FAP) to stand for the femtocell unit that contains base station and core network functionalities, and use femtocell to refer to the service area covered by the FAP.

As shown Figure 1, externally, a FAP looks like a WiFi access point (WAP). However, internally, they are fundamentally different. WAP implements WiFi technologies such as IEEE 802.11b, .11g, and .11n. FAP implements cellular technologies such as GSM/GPRS/EDGE, UMTS/HSPA/LTE and mobile WiMAX (IEEE 802.16e).

Figure 1. Some femtocell access points

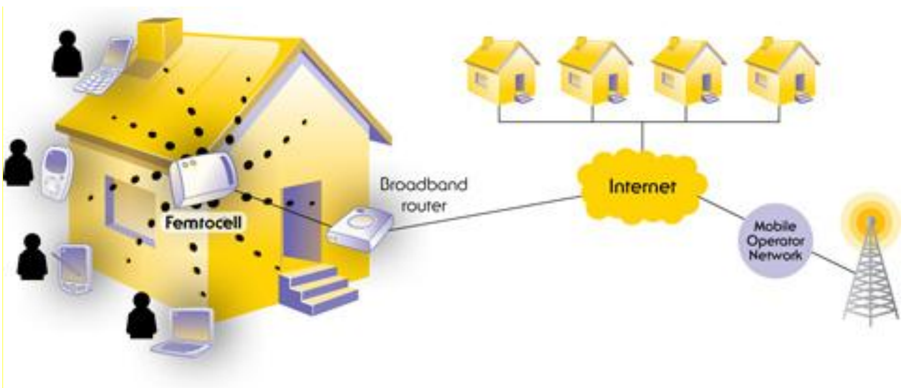

Figure 2. Femtocell connected to mobile network [www.femtoforum.org]

Why is femtocell important?

Femtocell is very important because of the following reasons:

- It can provide indoor coverage for places where macrocells can not.
- It can off load traffic from the macrocell layer and improve macrocell capacity (in the case of using macrocells to provide indoor coverage, more power from base station will be needed to compensate for high penetration loss and result in the decrease of macrocell capacity).
- Exponential growth in mobile data, yet the price to end user is being driven down by competition. Air interface spectral efficiency is not growing at sufficient rate to address the users and network operator's demands. The addition of a femtocell layer will significantly improve the total network capacity by reusing radio spectrum indoors. Focusing on topology to complement the technology is pivotal to address a number of key points such as cost (both CAPEX and OPEX), efficiency, ease of deployment and indeed the green side that small cells offer.
- Femtocells can provide significant power saving to UEs. The path loss to indoor FAP is much smaller than that to the outdoor macrocell base station, so is the required transmitting power from UE to the FAP. Battery life is one of the biggest bottlenecks for providing high speed data services to mobile terminals.
- As FAPs only need to be switched on when the users are at home (for home femtocells) or at work (for enterprise femtocells), the use of femtocell is "greener" than macrocells. The power consumption of base stations accounts for a considerable amount of an operator's OPEX.
- Femtocell provides an ideal solution for FMC (Fixed Mobile Convergence).

Challenges arising from femtocell deployment

The deployment of a large number of femtocells (in particular, spectrum-efficient co-channel deployment) will have an impact on the macrocell layer, and gives rise to many interesting and challenging research topics. **First**, randomly distributed femtocells will create interference to macrocell networks and also between themselves, this has to be thoroughly evaluated and controlled. **Second**, FAPs (Femtocell Access Points) are consumer electronics and must be able to plug and play; hence, they must be able to configure and optimise themselves with minimum interventions from users or operators. **Third**, the hybrid femto/macrocell network will generate challenging mobility management issues that are different from traditional two-tier networks. **Fourth**, there lacks a planning tool that can effectively evaluate the indoor ↔ outdoor scenarios. The first three challenges will be addressed in this WP (this deliverable will focus on the interference issue), the fourth challenge will be addressed by WP3 and WP1.

Among these challenges, interference analysis and mitigation are more urgent than others.

In the rest of this report (D2.2), interference analysis for femto/femto and femto/macro scenarios and related mitigation methods will be discussed.

Some femtocell related terminologies

For the sake of clarity, the terminology that will be used throughout this manuscript with regard to two-tier networks is presented in the following.

First of all, the main femtocell access policies are described:

- Closed access mode: Private access, also referred to as Closed Subscriber Group (CSG). Only some specific clients of an operator can connect to a given closed access femtocell. The list of allowed clients is regulated and modified in situ by each femtocell owner.
- Open access mode: All clients of an operator have the right to connect to all open access femtocells of this operator.
- Hybrid/limited access mode: a limited amount of the femtocell resources are available to all users, while the rest are operated in a CSG manner.

In addition, in closed access femtocells, users are classified as follows:

- Femtocell subscriber: A subscriber of a femtocell is a user registered in it, and they are usually terminals that belong to the femtocell owner, its family or its friends.
- Femtocell nonsubscriber: A nonsubscriber of a femtocell is a user not registered in it, and hence they are only allowed to connect to the network through the macrocell tier.

The types of interference in two-tier networks are classified as follows:

- Cross - tier interference: This refers to situations in which the aggressor, an FAP, and the victim of the interference, a passing macrocell user, belong to different tiers.
- Co - tier interference: This refers to situations in which the aggressor, an FAP, and the victim of the interference, a neighboring femtocell user, are of the same tier.

2 Interference Scenarios in Two-tier Femto/Macro Networks

In the co-channel deployment (it is preferred due to higher spectrum efficiency) two-tier femtocell/macrocell networks, there are both co-tier interference (femtocell ⇔ femtocell) and cross-tier interference (femtocell ⇔ macrocell). Interference scenarios in two-tier femto/macro networks are summarized in the following figure.

In 3GPP TR 25.820, the impact of HNB (Home NodeB)/ HeNB(Home eNodeB) on MNB (Macro Node-B/eNodeB) macro layer is identified with downlink emphasis and the prioritized interference scenarios are listed as below.

Table I: Interference Scenario analysis [3GPP TR 25.820**]**

Number	Aggressor	Victim
1	UE (User Equipment) attached to HNB	MNB Uplink (UL)
2	HNB	MNB Downlink (DL)
3	UE attached to MNB	HNB Uplink
4	MNB	HNB Downlink
5	UE attached to HNB	HNB Uplink
6	HNB	HNB Downlink

The above interference scenarios can also be shown in the following figure.

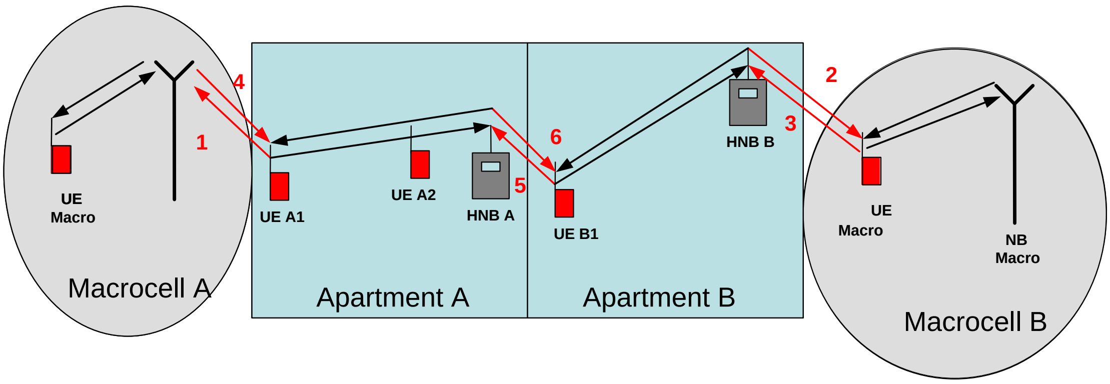

Figure 3: Interference scenarios [3GPP TR 25.820, www.3gpp.org]

Among them, interference scenarios 1-4 and interference scenarios 5 and 6 are for femto ⇔ macro and femto ⇔ femto respectively.

Interference scenario 1: UL HNB UE → Macro

In this scenario, as UE A1 is at the edge of HNB A, it will transmit at higher power which will generate significant interference to the uplink (UL) of Macrocell A. Noise rise on the macro layer will significantly reduce macro performance; consequently, the transmit power of the UE should be controlled and interference management techniques are required to manage the interference.

Interference scenario 2: DL HNB → Macro UE

In this scenario, as UE Macro is at the edge of Macrocell B, its received power from NB Macro will be relatively weak. On the other hand, it is close to HNB B; hence, UE Macro will receive significant interference from HNB B. In the case of a CSG HNB, downlink interference from HNB B will result in coverage holes in Macrocell B. In co-channel deployment the coverage holes are considerably more significant than when the HNB is deployed on a separate carrier. Interference mitigation mechanisms have to be considered to reduce the impact of the macro coverage.

Interference scenario 3: UL Macro UE → HNB

In this scenario, as UE Macro is at the edge of Macrocell B, it will transmit at high power; also, as it is close to HNB B, it will generate large interference to the UL of HNB B. As described in interference scenario 1, the HNB attached UE is constrained in its transmit power. Consequently, the HNB attached UE is especially susceptible to interference from the macro UE. The HNB receiver must reach a compromise between protecting itself against uncoordinated interference from the macro UEs, while controlling the interference caused by its own UE's towards the macro layer.

Interference scenario 4: DL Macro → HNB UE

In this scenario, as UE Macro is at the edge of HNB A, its received power is small. Hence, the interference from the DL of Macrocell A will become significant.

Interference scenario 5: HNB ←→ HNB (UL)

This interference scenario occurs in terraced houses and multi-floored apartment/office environment, where co-channel femtocells are deployed. E.g., one femto UE attached to a CSG HNB/HeNB is at the cell edge, where another CSG HNB/HeNB is installed very close to where the UE is. In the UL, UE B1will interfere with the neighbouring HNB A due to high transmit power that is needed to connect to HNB B (CSG).

In this scenario, interference management techniques are required to manage femto to femto interference.

Interference scenario 6: HNB ←→ HNB (DL)

Similar to interference scenario 5, this interference scenario occurs in terraced houses and multi-floored apartment/office environment, where co-channel femtocells are deployed. E.g., one femto UE attached to a CSG HNB/HeNB is at the cell edge, where another CSG HNB/HeNB is installed very close to where the UE is. In the DL, HNB A will interfere UE B1 due to close distance and the received power of UE B1 will be weak as it is at the edge of HNB B.

In this case, interference management techniques are required to manage HNB to HNB interference.

3 The Impact of Access Methods to Interference and System Capacity

3.1 Introduction

Access control methods impact the interference between femtocells and between femto and macrocells, hence the system capacity.

When the closed access method blocks the use of the femtocell resources to a subset of the users 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 bringing 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 in the quality of service of the femtocell owner.

Access control mechanisms play an important role to mitigate cross-layer interference and handover attempts, that is why they have to be carefully chosen depending on the customer profile and the scenario under consideration.

3.2 Simulation studies

In this section, the impact of open and closed access methods will be investigated. In the following, the simulation is based on the downlink of co-channel deployed two-tier WiMAX femto-macro networks. It should be noted that the results can be applied to the downlink of co-channel deployed LTE femto-macro networks, this is because on the downlink, both WiMAX and LTE use OFDMA for multiple access.

Figure 4 presents an aerial view of a residential area within Luton, a town located at the north of London (UK) where the study has been brought about. The location of the macrocell base station can be easily identified from the coverage plot in Figure 5. In order to study a dense FAP deployment scenario, most of the femtocells have been deployed in the same street.

The positions of such femtocells can be also checked in Figure 5, where some femtocells have been switched off for an easier visual inspection of their effects.

To perform this system-level simulation, different traffic maps have been used for indoor and outdoor environments. Regarding the user distribution, there is an indoor traffic map per femtocell and house, containing solely two randomly positioned users. On the other hand, there is an outdoor traffic map in the street of the femtocells, containing 10 randomly positioned users. This scenario corresponds to a worst case scenario, since the probability of having one femtocell per house from the same operator, and two simultaneously connected users per house is quite low.

In this scenario, femtocells operate in the same channel as an existing macrocell network (co-channel deployment). This solution is far more challenging in terms of interference avoidance, but it is also more profitable for the operator due to the higher spectral efficiency. The parameters of the system-level simulation are shown in Table II.

A. Public/Open access femtocells

Open access has been recently regarded [1] as one of the key requirements for the proper functioning of co-channel deployed UMTS femtocells. In UMTS, LTE and WiMAX femtocells, it might happen that an outdoor user receives a stronger signal from a nearby femtocell than from a far macrocell. Since with public access a connection is possible by means of the nearby femtocell, the far macrocell signal becomes a weak interfering signal, producing an acceptable SINR in most of the cases. This access scheme obviously benefits outdoor users, who are able of making use of nearby femtocells, reducing the overall use of system resources (power/frequency) and therefore interference. This is proven in Figure 6, where it is shown that the outdoor users are mostly successful, since they use a nearby femtocell to connect.

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B. Private/Closed access femtocells

Although the access method for deployed femtocells still remains an open question, customers surveys [2] show that private access is the most preferred method to be used. However, this approach imposes some interference problems to macrocell and femtocell users referred to here as the “street problem” (Figure 3). In the first street problem, a UL user connected to a near femtocell can be jammed due to the presence of a closer UL user connected to a macrocell using the same frequency/time slot (interference scenario 3). In the second street problem, a DL user connected to a far macro-cell can be jammed due to the presence of a closer DL user connected to a femtocell using the same frequency/time slot (interference scenario 2).

In Figure 7, it can be seen how the outdoor users connected to a far macrocell are jammed due to the interference coming from nearby femtocells. Due to these problems, interference avoidance techniques need to be applied to reduce the impact of femtocells into the macrocell. Some of these include Adaptive Femto Power (AFP), Dynamic Frequency Planning (DFP), and Adaptive Uplink Attenuation (AUA).

Figure 8 shows the computed probability distribution for the total cell throughput in both access modes. This figure evinces the fact that private access methods tend to drive the total cell throughput to values that are around 15% lower than a public access method. This is due to the destructive interference that indoor femtocells produce to the users that are connected to the macrocell. The decrease in the percentage of users without RAB (Radio Access Bearer) for the public access method is as well made evident in Table III. For a detailed performance metric comparison (number of attempted handovers in femto/macro, outages and throughput at both femto and macro layers) can be found in [3]

Fig. 4. Satellite view of the area subject to study (Luton, UK)

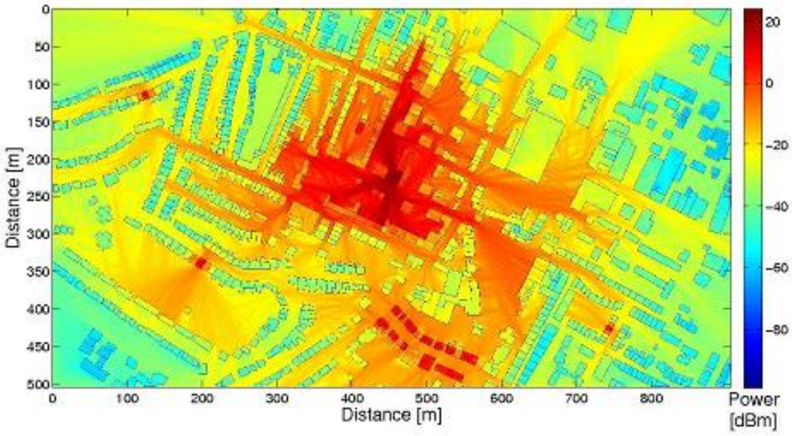

Figure 5. Best-server coverage in a hybrid macro-femtocell scenario with a densely deployed street and some randomly located femtocells

Table II Simulation parameters

Parameter	**Value**	**Parameter**	**Value**
Nr of Macrocells	1 Femto	Ant. Height	1m
Nr of Femtocells 32		Femto Ant. Tilt	0
Carrier Frequency	3.5GHz	Femto Noise Figure	4 dB
Channel Bandwidth	10MHz	Femto Cable Loss	3 dB
DL:UL Ratio	1:1	CPE Tx Power	23 dBm
Permutation Scheme	AMC	CPE Ant. Pattern	Omni
Frame Duration	5ms	CPE Ant. Height	1.5m
Sub-channels	16	CPE Noise Figure	5 dB
DL symbols	19	CPE Cable Loss	0 dB
BS TX Power	43 dBm	Service	Video

BS Ant. Gain	18 dBi	Min Service TP	64.0Kbps
BS Ant. Pattern	Omni	Max Service TP	128.0Kbps
BS Ant. Height	30m	Average Symbol Eff.	19.9Kbps
BS Ant. Tilt	3	σ(Shadow Fading)	8 dB
BS Noise Figure	4 dB	Intra BS correlation	0.7
BS Cable Loss	3 dB	Inter BS correlation	0.5
Femto TX Power	10 dBm	Snapshots	100
Femto Ant. Gain	0 dBi	Path Loss Model	FDTD
Femto Ant. Pattern	Omni	Snapshots	100

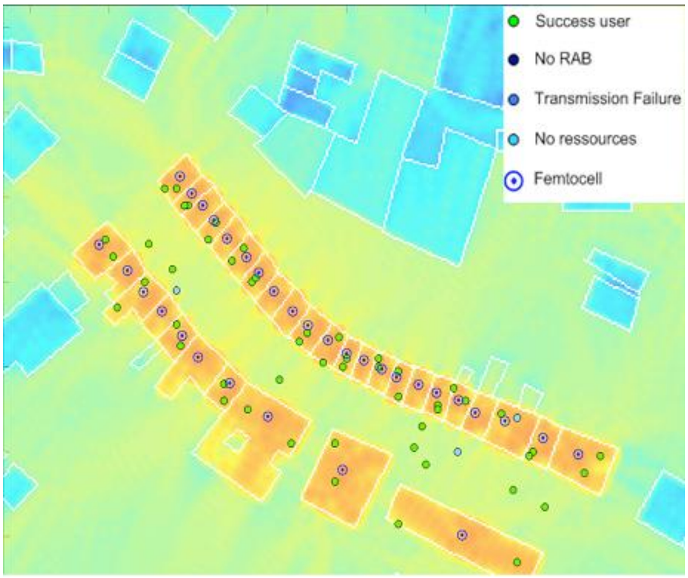

Figure 6. Downlink system-level simulation when using open access

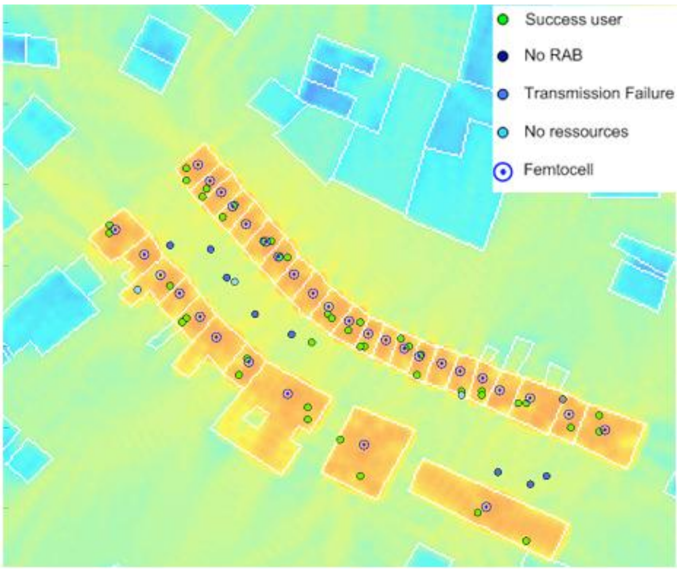

Fig. 7. Downlink system-level simulation when using closed access

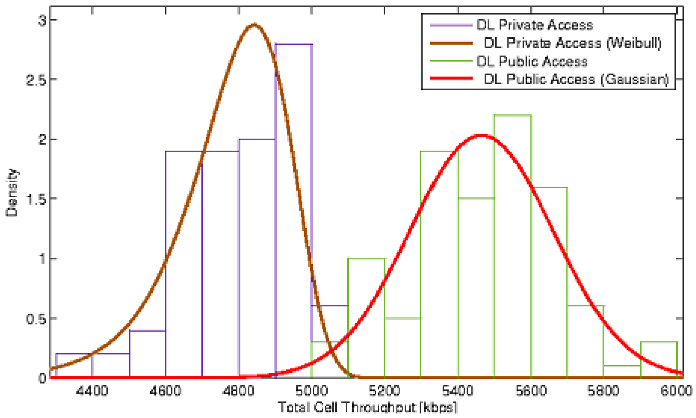

Fig. 8. Downlink total cell throughput PDF

Table III Access Method Statistics

	Public Access	Private Access
Users with errors in transmission	6.2%	6.8%
Users without RAB (Radio Access Bearer)	0.2%	6.8%

3.3 Conclusions

Throughout several numerical simulations, it has been indicated that a private (closed) access method would decrease the total cell throughput by around 15% with respect to a public (open) access. This would occur in exchange for the sharing of the femtocell resources with nearby users plus an increase in the number of HO (handover). Further results about the number of increased HOs are presented in [3] based on a dynamic WiMAX simulator. On the other hand, our simulations show that private access would increase the percentage of users with errors in transmission due to a lower signal quality. These users would be mostly outdoor ones who would suffer from femto-to-macro DL interference. However, this method is able of providing dedicated resources to its subscribers, avoiding the problems mentioned before.

Apart from public and private access (CSG in 3GPP term), hybrid access methods, with which a limited amount of the femtocell resources are available to all users, while the rest are operated in a CSG manner, have been also studied by us, more information can be found in [4, 3].

Since CSG is the preferred access methods by customer, this will give rise challenging interference avoidance tasks, which will be addressed in the next section.

4 The Investigation of Interference Mitigation Methods in OFDMA based Femto/Macro Networks

4.1 Introduction

In OFDMA based wireless networks such as WiMAX and LTE, intra-cell interference may be neglected due to the sub-carrier orthogonality features of OFDMA. Operators must therefore cope with inter-cell interference in order to enhance the network performance.

To overcome inter-cell interference, OFDMA networks are flexible in terms of radio resource management techniques, supporting different frequency reuse schemes and sub-channel allocation techniques, which in turn may decrease the inter-cell interference and increase the network capacity. However, these fixed schemes and techniques are not the most suitable solution in mobile scenarios, where the behaviour of the channel and the users are continuously changing.

Recently, the CWiND group in UoB developed Dynamic Frequency Planning (DFP) approach to the frequency assignment problem tailored to OFDMA networks. DFP can decrease the network interference and increase significantly the network capacity by dynamically adapting the radio frequency parameters to the environment. It operates on a regular basis to cope with the changing behaviour of the traffic and the channel throughout the day. DFP can run from a few times a day to on a second by second basis depending on the needs of the operator.

Within the iPLAN project, the DFP approach is extended to two-tier femtocell/macrocell scenarios to avoid interference between macrocell and femtocell as well as between femtocell and femtocell. System level simulation studies show that DFP can improve the network capacity and the user experience in outdoor and indoor scenarios.

In the following, the application of DFP in OFDMA based two-tier femto/macro networks will be discussed.

4.2 The application of DFP in OFDMA based femto/macro networks

When applying DFP, the process is divided in two parts: capacity and interference estimation and, frequency assignment optimization. Both of them will be briefly summarized in the following.

4.2.1 Capacity and Interference Estimation

Let us model an OFDMA network as a set of N sectors $\{S_1, S_2, S_i...S_N\}$, where each sector S_i requires a certain number of sub-channels D_i. The DFP problem consists on assigning a certain number of sub-channels D_i to each sector S_i, while minimizing the global system interference, taking into account interference restrictions between sectors. Since the number of required sub-channels is typically bigger than what is available, sub-channel reuse is needed. The sub-channel reuse leads to inter-cell interference.

The first key step is to estimate the number of sub-channels D_i required to satisfy the users bandwidth demand per sector. This can be estimated in regular basis, since each sector knows the number of connected user and their requirements in terms of capacity and throughput at each time.

The second key step is to characterize the inter-cell interference w[i, j] (the interference between sector i and j) between the sectors of the network. The model used for sensing the environment and estimating the interference is based on the User Measurement Report and the so called Restriction Matrix [5]. In this approach, it is considered hat two sectors, S_i (server) and S_j (neighbour), interfere with each other (interference $\text{event}_{i,j}$) every time the power level of the carrier signal (coming from S_i to a served user) is smaller than the power level of a neighbouring interfering signal (coming from S_j to the user) plus a threshold. The threshold is considered as a protection margin against interference and it is set by the mobile operator. The percentage of time of interference between both sectors S_i and S_j is calculated as the ratio between the total number of interference events and measurement reports. Note that this ratio does not accurately quantify the real interference between sectors, but it only characterizes it. The total number of interference events and measurement reports can be obtained from real measurement data or accurate path loss simulations. The higher the accuracy of the interference estimation is, the better the performance of the radio frequency planning will be.

4.2.2 The Dynamic Frequency Planning (DFP) Optimization Problem

Given a network defined by N sectors $\{S_1, S_2, S_i...S_N\}$ with D_i required sub-channels, NF available sub-channels $\{1, k...NF\}$, and the restriction matrix W[N,N] (note N is the number of sectors, hence, W[N,N] characterise the interference between all the sectors in the network being studied), the optimization problem can be defined as a Mixed Integer Program (MIP) as follows, where the target is to find the optimal solution that minimizes the given cost function representing the overall network interference.

$$min \sum_{i=0}^{N}\sum_{j=0}^{N}\sum_{k=0}^{K}\frac{W_{i,j}}{D_i D_j}y_{i,j,k} \qquad (1)$$

Subject to:

$$\sum_{k=0}^{K} x_{i,k} = D_i \qquad \forall i,k \qquad (2)$$

$$x_{i,k} + x_{j,k} - 1 \leq y_{i,j,k} \qquad \forall i,j,k \qquad (3)$$

$$y_{i,j,k} \geq 0 \qquad \forall i,j,k \qquad (4)$$

$$x_{i,k} \in \{0,1\} \qquad \forall i,k, \qquad (5)$$

where $x_{i,k}$ indicates that sector S_i uses frequency k. Constraint (2) imposes that sector S_i must use D_i sub-channels. Inequalities (3) and (4) together force that in an optimal solution $y_{i,j,k} = 1$ if and only if both sectors S_i and Sj use frequency k and $y_{i,j,k} = 0$ if otherwise. Finally, the cost function is the sum of the interference between all pair of sectors S_i, S_j taking into account all the frequencies *k*. Since the capacity of the sectors is not considered when the restriction matrix *W[N,N]* is built, the interference restrictions $w_{i,j}$ ($w_{i,j}$ represents the interference between the ith and jth sectors) must be divided by the number of used sub-channels D_i, D_j for both sectors S_i, S_j . In this way, the percentage of time in which both sectors S_i and S_j are transmitting with the same frequency *k* is estimated.

A number of approaches can be used to find the optimal or at least a good solution for the DFP problem in a femtocell environment. For example, Integer Linear Programming (ILP) can find optimal solution, but takes a long running time, meta-heuristics based methods such as simulated annealing (SA) and taboo (tabu) search (TS) can find solutions of good quality with a reasonably short time. However, both algorithms need to be properly tuned; also their performance depends on the parameter selection. Some greedy algorithms can find solutions in very short time. Because in the future this optimization will run on the femtocell itself, the trade-off between the qualities of the solution and the running time should be taken into account. Our studies show that ILP is not suitable for the implementation in FAPs. Note that meta-heuristics will find higher quality solutions than greedy algorithms, but at the expense of longer running times. However, the faster the optimization method, the more responsive the system can be to the changes of the traffic. It has been proven in [5] that when using DFP in an on-line scenario, it may be worth using faster algorithms since they produce only slightly worse solutions. Our simulations in two-tier femto/macro networks also confirm this finding.

4.2.3 Case study

This section presents an experimental evaluation of the proposed DFP solution for inter-cell interference avoidance in hybrid OFDMA based macrocell and femtocell environments.

4.2.3.1 The Description of the Scenarios

The scenario used for this experimental evaluation is Cardigan Street and its surroundings (the street in the centre of Fig. 9), Luton, UK. A non-uniform deployed WiMAX hybrid network formed by 1 macrocell and 30 femtocells is used for this case study. The 30 femtocells have been located in 30 different households of this street, corresponding to a worst case scenario in terms of interference, since every household has a femtocell. To perform the system level simulation, different traffic maps have been used for indoor and outdoor environments. There is one indoor traffic map per femtocell and house, containing 2 randomly positioned users. There are three different outdoor traffic maps with three different user densities: 3, 5 and 3 users, respectively.

This case study makes use of a private access method (CSG) for each femtocell. Indoor users will therefore connect to their femtocell or to the macrocell, and outdoor users will only do it to the macrocell. Only DL is studied for simplicity.

The environment and parameters of the system level simulation are the same in Table II.

Fig. 9. Considered scenario in Luton town center.

4.2.3.2 DFP Solving Strategies

Two assumptions have been taken for the sake of simplicity to solve the DFP problem. The DFP solving algorithm is based on a centralized network architecture, where a centralized entity should collect the data, generate the plan and distribute the information. On the other hand, the DFP solving algorithm runs on a per second basis, where meta-heuristics such as SA (Simulated Annealing) or TS (Taboo Search) can be used to solve the problem.

4.2.3.3 Channel allocation methods

In the following, the used sub-channel allocation strategies are summarized. Note that the first four methods (given for comparison) cannot be considered as optimized solutions since they are based on a random or pre-configured solution. However, the last two methods are based on DFP that is solved by SA.

- Same Channel Fragment: This corresponds to the worst case scenario where all the femtocells use the same group of sub-channels from the palette of available sub-channels. (4 fixed sub-channels per cell are taken from the 16 available).
- Random allocation: The sub-channels of all the femtocells are randomly chosen from the palette of available sub-channels. (4 random sub-channels per cell are taken from the 16 available).

- FRS 1X1X3: The palette of available sub-channel is divided in three sub-groups. Then, neighbouring femtocells are assigned to different sub-groups, reducing the probability of interference. Afterward, each femtocell can only get sub-channels from its given sub-group. (the 16 available sub-channels are divided in 3 sub-groups, the each sub-group is assign to one femtocell).
- Femtocell Optimization: An SA optimization method is used to solve the DFP problem. In this case, only the sub-channels of the femtocells are planned.
- Femto and Macro optimization: An SA optimization method is used to solve the DFP problem. However, here not only the sub-channels of the femtocells are planned, but also the macrocell. The resulting solution is the best case and it can help to evaluate the quality of the previously described methods.

4.2.3.4 Simulation results

The performance of the resulting sub-channel allocation strategies has been evaluated with system level simulations.

The results are shown in Fig. 10 and summarized in Table IV. It can be seen from the simulation that when the same sub-channels are allocated to all the femtocells (Unique sub-channels), the interference of the system is high (see Cost Function). In this case the performance of the system is degraded (see Total Throughput) and more users are set to outage. Note that the sub-channels of the macrocell are fixed and cannot be changed.

The performance of the system improves when the sub-channels of the femtocells are randomly chosen from the palette of available sub-channels. It is verified that an unlucky random allocation in which neighbouring femtocells use the same sub-channels performs worse than a lucky random allocation in which neighbouring femtocells use different sub-channels.

When a fractional reuse scheme is used (FRS 1x1x3), the interference of the system notably decreases compared to the worst method by around 95%. As a result, the total throughput and the number of satisfied user increases by around 45% and 95% respectively, compared to the same method.

Finally, when using optimization (last two methods), the interference is further reduced and the system performance improved. When all the femtocells are planned using DFP and the macrocell frequencies are fixed, a notable improvement is achieved compared with the worst method in terms of interference (99%) and therefore, in terms of total throughput (50%) and success users (95%). Compared to the FRS method, the cost function has been reduced around 85% and the total throughput and success users increased around 7% both.

However, the best result is obtained when not only all the femtocells are planned with DFP, but also the macrocell. In this case, the interference is quite small and the result is close to the free interference assignment, with all users successful.

Therefore, the results confirm that the better the resource allocation strategy is, the bigger the interference avoidance and the better the system performance will be.

It needs to point out that similar results will hold for two-tier LTE femto/macro networks[8].

TABLE IV SYSTEM LEVEL SIMULATION RESULTS

Method	Number	Success	No	Transmission	No re-	Total	Cost

	of users		RAB	Failure	sources	Throughput (kbps)	Function
Same Channel Fragment	63	3	28	4	0	3168.0	2256.0
Unlucky Random Allocation	63	46	10	7	0	4752.0	607.9
Lucky Random Allocation	63	54	9	0	0	5702.0	325.7
FRS 1x1x3	63	56	3	0	4	5913.6	143.5
Femtocell Optimization	63	60	0	0	3	6336.0	22.5
Femto and Macro Optimization	63	63	0	0	0	6652.8	12.5

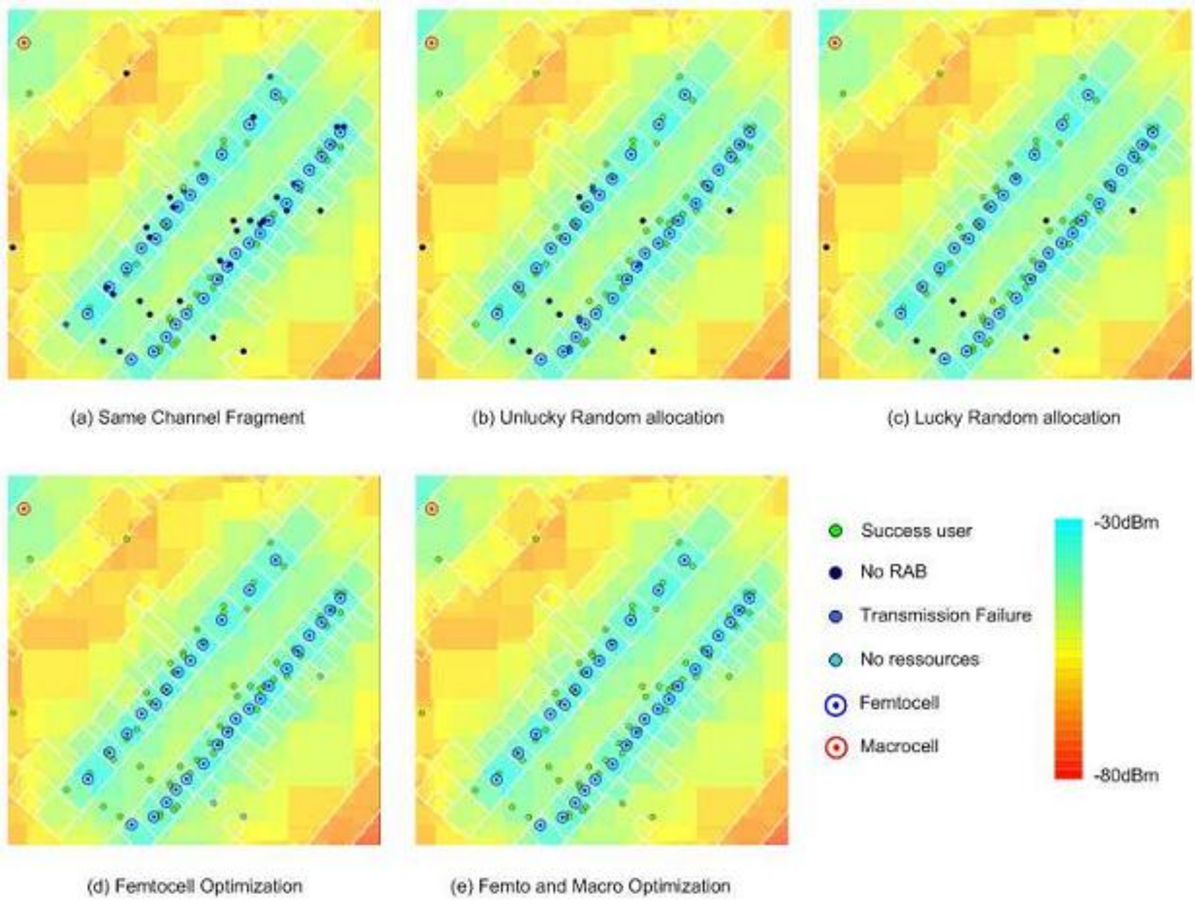

Fig. 10. System level simulation results

4.2.4 Conclusions and Discussions

It is demonstrated that DFP can be used to mitigate the inference in OFDMA based (such as WiMAX and LTE) two-tier femto/macro networks.

The approach can be extended to combine both sub-channel and sub-carrier power assignment or to combine sub-channel, power and MCS (Modulation and Coding Scheme) assignment to mitigate the inference in OFDMA based (such as WiMAX and LTE) two-tier femto/macro networks. Further work can be found in [6, 7].

The ideas presented here depend on a centralized network architecture, where a centralized entity should collect the data, generate the plan and distribute the information. However, a distributed architecture where each femtocell is able to select its own sub-channels would be more suitable. Further work can be found in [9].

5 Conclusions

In this deliverable, first, an introduction to femtocell and the challenges in two-tier femto/macro networks are summarised; second, the interference scenarios in two-tier femto/macro networks are discussed; third, the impact of access methods in terms of interference and system capacity in two-tier OFDMA based femto/macro networks are assessed through system level simulations; fourth, various channel allocation strategies are compared and DFP (Dynamic Frequency Planning) is investigated for inter-cell interference mitigation in two-tier OFDMA based femto/macro networks, simulation results show that DFP can effectively reduce interference and improve system capacity; finally, the report refers to further work by the CWiND team in joint sub-channel, power, and MCS allocation methods.

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