Performance of Open Access Femtocells in 4G Macrocellular Networks*

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***Abstract*—This paper examines the open access operation of femtocells within a macrocellular network in which the same spectrum is available to both types of basestation. We examine the RF performance, particularly the interference levels, and using a generic 4G wireless protocol show the data rates that can be achieved. We present a mechanism to improve the data rate distribution, and consider the impact of changing the density of deployed femtocells.**

***Index Terms*— Data rate; Femtocells; Macrocell networks; 4G Wireless**

I. INTRODUCTION

In both 3G and 4G systems, one area of current interest is the use of low power, self- deployed base stations for domestic and enterprise environments. These are sometimes known as 'Femtocells', and in the 3GPP (3rd Generation Partnership Project) standards organisation as 'Home e-Node Bs'. There is considerable interest in exploring the ways in which these femtocells should be operated and the benefit that can be achieved from using them. In this paper we analyse a representative deployment of femtocells within a macrocellular network where the available spectrum is used by both the macrocell and femtocell users. This ensures that the femtocells, in addition to being potential basestations, act as an additional source of interference to users.

The focus of this analysis is to understand how femtocells can be made to work in this Radio Frequency (RF) environment and the benefit which can be obtained by using them. When the same radio spectrum is used by both macrocells and femtocells, the unplanned nature of the femtocell deployment poses challenges to network operators running the existing macrocellular network. To understand this RF problem we analyse (through simulation) the representative deployment of femtocells in a macrocellular network with a 4G air-interface protocol. We restrict ourselves to a consideration of downlink (basestation to mobile user) transmission only.

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II. SCENARIO

A. Macrocellular Network

The simulation model used is based on a regular hexagonal grid of tri-sectored base stations, into which a set of femtocells is introduced randomly onto a grid of locations spanning a complete tri-sectored base station region, as shown in figure 1. Statistics of RF power and interference are acquired within this region, thus reflecting the full range of RF locations where a user could be present. The performance has been compared with the user performance for the macrocellular only network.

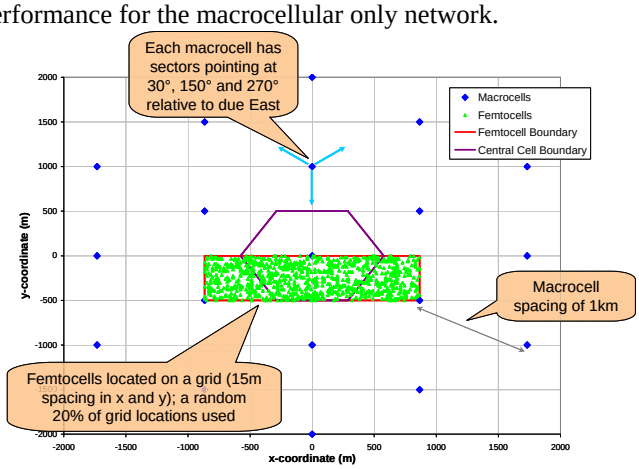

Fig 1: Illustration of scenario explored

B. Femtocell Distribution

We set the density of households with an active femtocell to a realistic figure of 20%; this corresponds to approximately 790 femtocells active within the deployment area (spanning the area covered by a tri-sectored basestation, equivalent to a circle of approximately 740 m radius). The femtocell locations are chosen at random on points on a grid with interval 15 m in both the x- and y-directions, representing the typical spacing of houses. Analysis of the impact of femtocells focuses on the signal to noise and interference ratios (SNIR) and the effective data rates (EDR) seen by users placed within the femtocell deployment region. The simulation model neglects thermal noise, the interference from the macrocells and femtocells is considered to dominate the unwanted noise power. Users are distributed randomly through the network, with a density of approximately 200 per macrocell sector.

C. Air Interface Protocol

To simulate the air interface protocol, SNIR values are converted to raw data rate using a representative

characteristic (from 3GPP standards [1]) which is shown in figure 2, together with the theoretical Shannon capacity. This requires a minimum SNIR value of -10dB for there to be any data throughput and has a maximum data rate of 4.4 bits/s/Hz. Spectral resource is then split evenly across all the users connected to a given server (either macrocell or femtocell). That is, all users connected to a given cell receive the same proportion of time slots. The effective data rate seen by a user is therefore the raw data rate scaled by the proportion of time slots dedicated to that user. The resulting effective data rates therefore depend upon the SNIR seen by that user and the number of other users associated with that same serving cell.

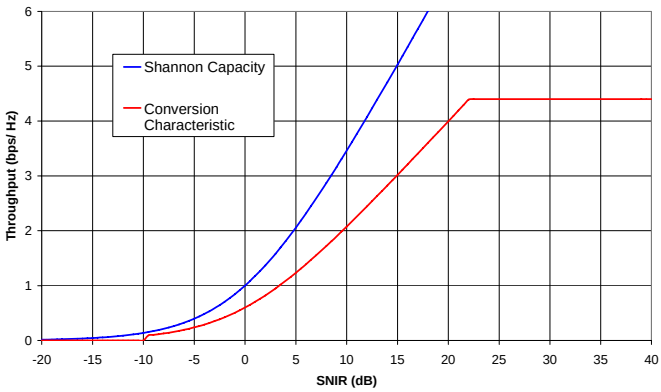

Figure 2: SNIR to Throughput conversion characteristic used in analysis

Representative single slope median path loss models were used to determine the received signal levels. For the macrocell to user propagation, this is based on the COST Hata model with a correction for UE height, which varies approximately as $r^{3.5}$. For the femtocell to user propagation, the model has a slope corresponding to exactly $r^{3.5}$, but with a higher path loss at any given range to reflect the signal loss through building walls. This reflects the fact that femtocells will in general be located indoors, whereas in an open access scheme we expect users both inside and outside buildings to use the femtocells. Both of these path loss models are shown in figure 3; signal transmission frequency is 2 GHz. A log normal standard deviation of 10dB was used with these path loss models; the bulk of results presented here incorporate this realistic level of log normal shadowing, although some of the EDR distribution maps show the results without log normal shadowing to ease comprehension of the mechanisms at work.

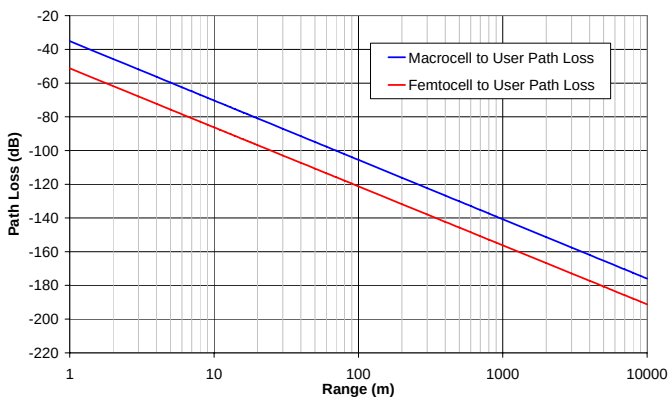

Figure 3: Path loss models for Macrocell and Femtocell to user propagation

Transmit powers of +43dBm and +24dBm respectively are used for all the macrocells and all the femtocells in the system. The macrocells have tri-sectored antenna patterns, with beams pointing at 30° (approximately NE), 150° (approximately NW) and 270° (S) with peak gain of approximately 14dB, and a backlobe level of -6dB. (This is sometimes referred to as a tri-cellular arrangement). The femtocells have an omni-directional antenna gain of 0dB.

III. SIMULATION RESULTS

In this paper we only consider Open Access operation for the femtocells. By Open Access we mean a scheme whereby users can select femtocells as a direct alternative to a basestation from the macrocellular network, without requiring any specific registration etc. In the first instance, we explore the impact of introducing the femtocells into the macrocell only network where users select the best server based on the highest received SNIR.

A. *Impact of Femtocells*

The introduction of femtocells into the network makes a significant difference to both the SNIR and the EDR seen by a user. The additional femtocells contribute to increased interference and hence reduced SNIR for the vast majority of users, as shown by the cumulative distribution functions in figure 4, which is for an environment with 10dB log normal shadowing, and femtocells in 20% of homes.

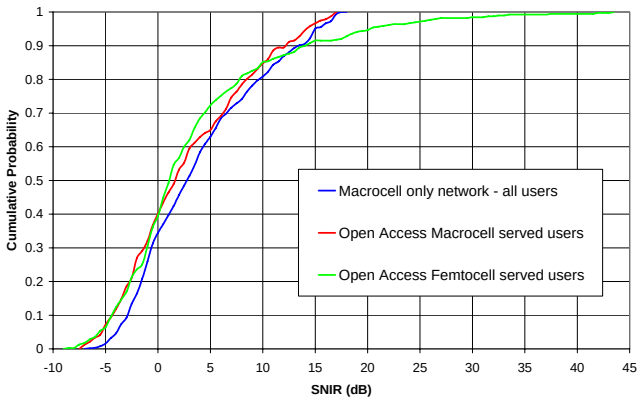

Figure 4: Cumulative SNIR distributions for macrocell only network and open access operation of the femtocells within the macrocell network, users classified by server type. Model includes 10dB log normal shadowing, and femtocells occur in 20% of homes

Compared with the macrocell only network case, all users who continue to be served by macrocells when femtocells are introduced into the network see a reduced SNIR due to the increased interference from the femtocells. Around 85% of femtocell served users see a reduction in SNIR over the macrocell only case; only those users which are very close to a femtocell see an improvement in SNIR – an improvement which can be in excess of 15dB.

There is however a strong contrast with the EDR experienced by users. As the cumulative distribution functions in figure 5 show, again for a 10dB log normal shadowed network and a 20% femtocell density, all users see some improvement in their data rates despite the increased interference.

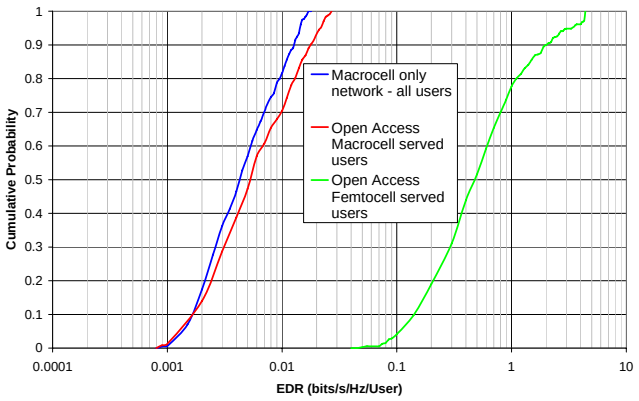

Figure 5: Cumulative EDR distributions for macrocell only network and open access operation of the femtocells within the macrocell network, users classified by server type. Model includes 10dB log normal shadowing, and femtocells occur in 20% of homes

For those users who continue to be served by the macrocells, the reduced loading on the macrocells allows users to get more time slots for transmission of data. This offsets the impact of the reduced SNIR (due to the increased interference from the femtocells), and hence lower raw data throughput, seen by those users. Thus, macrocell served users can see an increase in their effective data rate. Users that choose to be served by the femtocells see increases of 2-3 orders of magnitude in their EDR over the macrocell only case. This is because they are typically the only users being served by that femtocell, getting the full set of available time slots. This increases the data rate significantly despite the lower SNIR (and hence lower raw data rate) resulting from the random deployment of the femtocells. For users very close to the femtocells, the very high SNIR they experience allows the data rate to be very high, subject to the limits of the modulation scheme.

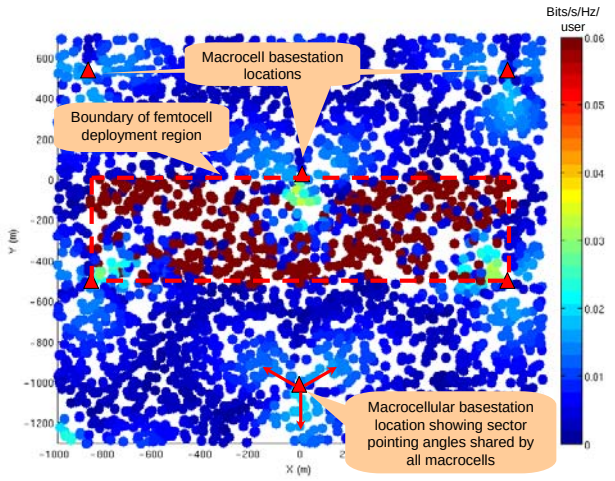

Figure 6: Effective data rates in a portion of the macrocell network that includes the femtocells

Figure 6 shows the distribution of effective data rates in bits/s/Hz/user for the femtocell deployment in 20% of households, the femtocells placed in the 'letterbox' region of the regular macrocell network as shown in figure 1. One dot represents one user, and log normal shadowing has been omitted in this figure for clarity. Note the significant improvement in data rates enjoyed by users near the femtocells and in the main beams of the macrocell sectors that span the femtocell deployment region. We observe that for a 20% active femtocell density and a realistic degree of log normal shadowing, around 60% of users select femtocells and the remaining users are served by the macrocells.

IV. ENHANCED CELL SELECTION TECHNIQUE

As the results in section III have shown, data rates improve for users if they are served by femtocells. Furthermore, when femtocells are deployed with open access operation this permits higher data rates for the macrocell served users through the reduced loading on the macrocells. Thus, any technique which actively promotes users from macrocells onto femtocells is advantageous from a data rate perspective. With open access operation, one way to do this is to change the cell selection scheme. We propose a novel technique using the effective data rate (EDR) rather than received signal strength, as is more conventionally used, to decide on the cell to which a user should be connected.

A. Simulation Results for EDR Based Cell Selection

Users seeking to connect to a cell categorise the cells that that are visible to them before selecting which cell to which they request connection. Conventional networks use the cell from which the user gets the highest received signal (equivalent to the highest SNIR offered by the cells) as the cell from which a user requests service. When EDR based cell selection is used, the user chooses the cell which can offer the highest effective data rate. A cell which offers a more modest SNIR (and hence lower raw data rate than a cell offering the highest SNIR) but which is only relatively lightly loaded, may offer a higher effective data rate. It is from this lower SNIR but higher EDR cell that a user would request service.

Figure 7 shows the SNIR distributions, split by server type, for best EDR and best SNIR based cell selection schemes for a 20% active femtocell density, and a realistic figure for the log normal shadowing in the environment.

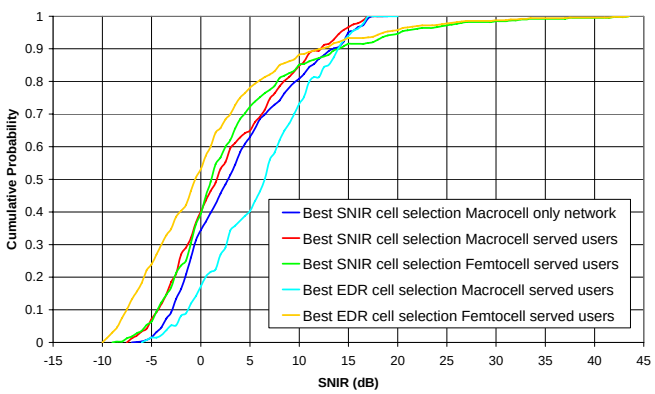

Figure 7: Cumulative SNIR distributions for Best SNIR and Best EDR cell selection methods split by server type. Model includes 10dB log normal shadowing, and femtocells occur in 20% of homes

The use of EDR as the cell selection metric promotes users from the macrocells to the femtocells if a higher effective data rate (not *necessarily* raw data rate) can be achieved by a femtocell. As a result, the SNIR of users served by femtocells tends to be reduced as the macrocell

users who are promoted to a femtocell move to a femtocell which offers lower SNIR but which is only very lightly loaded and hence can offer an increased effective data rate. The users which are left on the macrocells tend to be those with higher SNIRs whereby the EDR they experience is higher than they could get from any of the femtocells in the network.

A plot of the EDR achieved in the part of the macrocell network where femtocells are deployed is shown in figure 8. This should be compared directly with figure 6, which shows the same scenario but employs Best SNIR as cell selection metric.

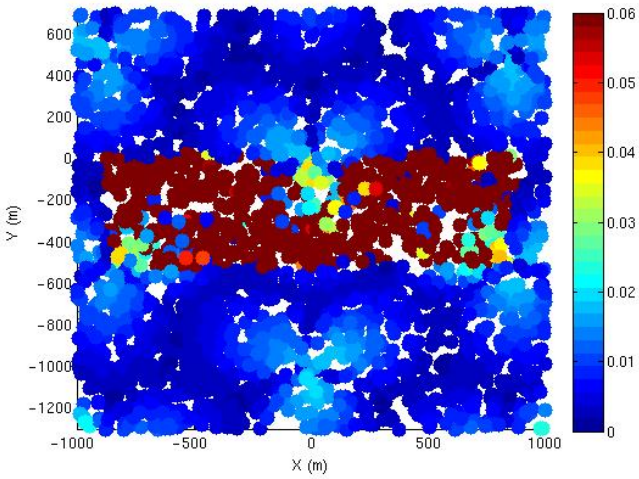

Figure 8: Effective data rates in a portion of the macrocell network that includes the femtocells when Best EDR cell selection is used

As figure 8 shows, the high data rates offered by the femtocells are much more widespread in the femtocell deployment region as more macrocell users are off-loaded to the femtocells. In addition, in the main beams of the macrocells, the data rates increase as fewer users are now connected to the macrocells and those that remain get a greater proportion of the time slots and hence higher data rates. Note that as with figure 6, log normal shadowing has been omitted for clarity.

The distribution of data rates is shown in figure 9 for the two different cell selection mechanisms, for a 20% femtocell deployment density and 10dB log normal shadowing in the network. As implied by the SNIR distributions in figure 7, the users left on the macrocells when selecting by best EDR see improvements in their data rates as their combination of high SNIR and lower cell loading cause their data rates to improve. Using the EDR based handoff technique, the distribution of data rates of the femtocell served users is reduced somewhat because the significant number of macrocell served users promoted to femtocells increases the femtocell loading. This reduces the available data rate that a user connected to a femtocell can achieve, as the spectral resource is split among a greater number of users. The data rate increase for femtocell served users is still, however, very large over the data rate that users in a macrocell-only network can experience.

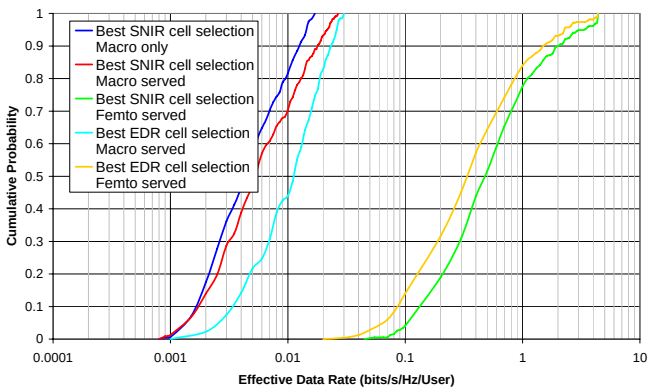

Figure 9: Cumulative EDR distributions for Best SNIR and Best EDR cell selection methods, split by server type. Model includes 10dB log normal shadowing, and femtocells occur in 20% of homes

The use of EDR for cell selection increases the proportion of users served by the femtocells to around 80%, compared to 60% when the best SNIR is used as the cell selection criterion.

An alternative way to analyse this data is to create a cumulative distribution of *all* users in the network, irrespective of server. Figure 10 shows this for this same scenario.

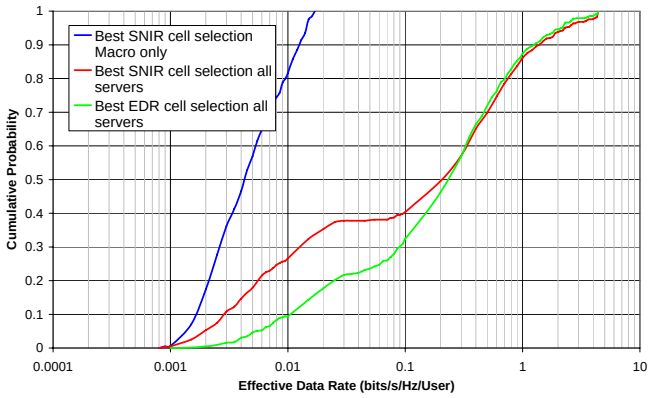

Figure 10: Cumulative EDR distributions for Best SNIR and Best EDR cell selection methods. Model includes 10dB log normal shadowing, and femtocells occur in 20% of homes

Analysis of the data rate distributions in figure 10 shows that users in the lowest part of the distribution see the greatest improvement in their data rate by changing the cell selection scheme from Best SNIR to Best EDR. For users at the lowest 10% level of the distribution, using the best EDR to select server improves the data rate by a factor of around 3.7 times, for an active femtocell density of 20%, over that from the conventional best SNIR based cell selection technique. The greatest benefit of the EDR cell selection technique is thus for those users which are most poorly served in terms of data rate.

B. Impact of Changing Active Femtocell Density

From an operator's perspective it is important that the benefits of having femtocells in a macrocellular network can be exploited from relatively low deployment densities. Figure 11 shows how the split between macrocell and femtocell served users varies as the femtocell density is varied from 0% (macrocell only network) to 40% femtocell density, for both the Best SNIR and Best EDR cell selection

mechanisms. These results are for scenarios in which the log normal shadowing is 10dB. It can be seen that an active femtocell density of approximately 10% of households will ensure that half of all macrocell users are displaced onto the femtocells.

The use of EDR cell selection ensures that a lower density of femtocells are required to off load half of all macrocell users onto the femtocells than with an SNIR based cell selection technique. Additionally, it is at the lower femtocell densities that the benefit is most rapid, that is, as the femtocells are initially being rolled out into the existing macrocellular network that the greatest gains in off loading – and hence data rate improvements – will be seen, benefiting both the cellular operator and network users.

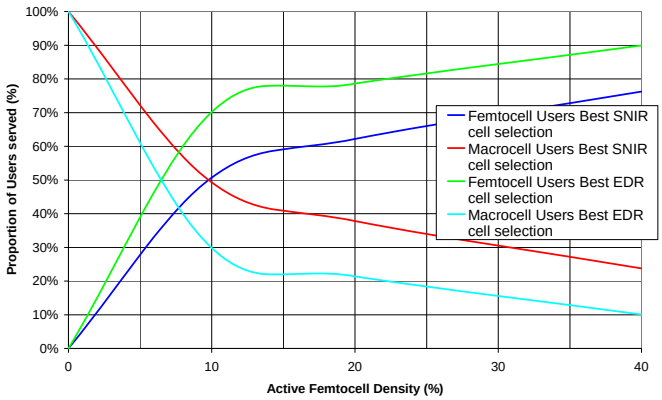

Figure 11: Split of users as active femtocell density is varied in scenario Model includes 10dB log normal shadowing

Analysis of the macrocell only network using the Best SNIR and Best EDR cell selection methods has shown that using EDR as cell selection metric provides a valuable load balancing function where the Best SNIR cell selection results in uneven cell loading figures.

V. KEY CONCLUSIONS

Open access femtocell deployments can provide significant benefits in capacity and user data rates to conventional macrocellular networks. Our detailed analysis has shown that:

There is a significant data rate improvement for a user when they connect to a femtocell which has been included within a macrocell network. This data rate improvement can be up to 2-3 orders of magnitude.

Macrocell served users also experience an improvement in data rates as a result of the off-loading of users on to femtocells.

An active femtocell density of approximately 10% of households will enable around 50% of users to be off-loaded from the macrocell network.

The use of the best EDR metric for cell selection is a very powerful technique for promoting users on to femtocells, where their data rates are improved despite a reduction in the SNIR they experience. For users remaining on the macrocells, the significantly reduced macrocell loading figures that result leads to significant increases in their data rates.

The greatest benefits in the use of EDR based cell selection are targeted on the most poorly served users in the network – with the lowest 10% of users seeing an improvement of up to 3.7 times in their data rate.

REFERENCES

[1] 3rd Generation Partnership Project, "Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access; Radio Frequency system scenarios (Release 8)," 3GPP TR 36.942 v1.2.0, 2007, Annex A.1.

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