Power Efficient Femtocell Distribution Strategies

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***Abstract*—Reducing our power consumption is an urgent issue which has important economical and ecological benefits. By using femtocell technology the mobile network can become far more energy efficient than it is today. In this paper, we describe what femtocell technology is and introduce outdoor femtocell distribution strategies that can save the network power. We also compare the usage of typical short-range base stations in place of femtocells and show that femtocells are more efficient. The results of the introduced strategies show that significant power savings of up to 92% can be achieved on a per-macrocell basis if implemented.**

1. INTRODUCTION

The mobile phone industry has some great challenges in the road ahead. With the data rate demands expected to grow 26 fold by 2015 and the influx of mobile subscribers across the globe [1], new telecommunication infrastructure will need to be laid down in order to satisfy consumer needs. This extra infrastructure will have to be in the form of smaller cells because, in accordance to Shannon's Law, there is an upper bound in the amount of information that can be transferred in a communications channel and it is dependent on the signal's bandwidth and signal to noise ratio (SNR). It is known that we are reaching that boundary. The chief executive of Qualcomm has been quoted saying "the improvement of wireless links that enhance user throughputs is reaching its limit" [2]. This means that more efficient coding and modulation is becoming closer and closer to a dead end with regards to improving data rates.

In addition, the high end-user densities also pose the issue of not being able to supply users the proper quality of service (QoS) not only in terms of data rates but even a simple voice connection due to the increasing loads on local macrocells. To clarify, a standard macrocell base station (mBS) transmits on only a few distinct licensed channels per mobile operator [3]. Therefore, only a certain number of users can be connected to a single macrocell at once. This is in effect the result of a lack in spatial efficiency.

Both of these issues lead to one conclusion proposed in the papers [4], [5] and [6]; current mBS cells providing coverage to increasingly 'popular' districts will need to be broken up into smaller cell sizes in order to take advantage of spatial reuse. However, the result of this additional infrastructure is additional power consumption. The additional power that will be consumed is not only costly to the operator due to the increasing electricity prices [7], but it is also costly to the environment due to the resulting greenhouse gases [8].

Since the global information and communication technologies (ICT) already contribute 2% of the world's greenhouse gas emissions, it would not only be economical to reduce the energy consumption but ecological as well. However, it is a necessity to provide consumers with proper data rates in densely populated areas regardless of the situation.

The aforementioned papers show how reducing cell sized can save energy and increase data rates. In this paper we propose taking that research one step further by using a relatively new technology called femtocells. By strategically distributing base stations that use femtocell technology instead of other base station technologies the network's power consumption can be reduced drastically.

A femtocell is a dynamic low powered base station transceiver that operates in the licensed frequency spectrum of the macrocell network, and is (in most cases) deployed by the end-user (unlike all other base stations). It can be available in all the common technologies but currently the focus has been on 3G since 4G has not yet been deployed extensively. The typical femtocell provides about 20 dBm of radiated power and only consumes 4.5 to 13.5 watts [3], [9]. The primary usage of femtocells today is to provide indoor voice and data coverage in the numerous dead-zones experienced by end-users at home or at the office [10].

One of the defining features of femtocells is that they are backhauled over an internet connection (ADSL, cable, fiber...) [3] to the macrocell network unlike other base stations. This is done through the femto gateway (FGW) which is the link that communicates with the femtocell access points (FAPs) over the internet and securely joins them with macrocell network.

Since femtocell technology allows for back hauling over the internet, these base stations are passively cooled and consume very small amounts of energy [11]. This is what makes femtocell technology a prime candidate for our research in energy efficient macrocell coverage segmentation. In section 2 of this paper we will propose two possible energy efficient outdoor femtocell (OF) distribution strategies and derive their results mathematically. Each of the results will be analyzed and compared to provide a figure for their energy efficiencies.

2. OUTDOOR FEMTOCELL POWER EFFICIENCY STRATEGIES

Until today smaller cells, such as microcells and picocells, have been distributed by operators to increase their network's capacity in areas of high user densities. However, these base stations are generally back hauled to the mobile network the same way mBSs are and therefore consume more energy than femtocells.

The advantage of low power consumption that femtocell technology provides can be used to make the current mobile radio network expend less energy. If providers deploy OFs in an effective manner then enormous power savings could be attained by relieving the mBSs which consume far more energy.

We have researched two possible strategies for distributing OFs in a manner that will take advantage of their low power consumptions. In Section 2.1 and 2.2 we will discuss and evaluate the strategies of 'femto-bordering macrocells' and 'femto-gridding' respectively. Later on in section 2.3 we will also show how femtocell technology is more effective in saving energy than other short-range base stations.

It should be noted that in our research, we view all short-range base stations that are back hauled over the internet as femtocell technology since this is one of the defining features of femtocells. Therefore, picocell base stations that are back hauled over the internet will be considered to be femtocells in this paper.

In our calculations we will be using an OF designed by Ubiquisys [9] as a reference for our calculations. Table 1 lists all of the parameters and assumptions we have taken into account for the following sections.

2.1 Femto-Bordered Macrocells

The strategy is to segment the coverage along the borders of macrocells with OFs to relieve the cell's power consumption. This idea comes from the common knowledge that mBSs need to expend power levels at an increasing exponential rate to their power amplifiers (PAs) in order to reach further distances [12]. By placing femtocells in the outer limits of the macrocell's coverage a considerable amount of energy can be saved by relieving these local mBSs. These OFs, that consume very few watts of power, can be in charge of these 'sticky' areas of the grid and all handovers that preside within. As a result, the local mBSs' PAs would then need exponentially less energy to cover the shorter ranges expressed as a star like shape in Fig. 1 (note that the radii in Fig. 1 depict the maximum path losses of the cells). Furthermore, the mBS’s new processing overhead would be less as well since the new star shaped coverage area would encompass fewer users than before. Lastly, given that the radio components of a mBS uses 80% of a mBS's total power consumption (50% of which is the PA) [13] a great deal of energy will be saved.

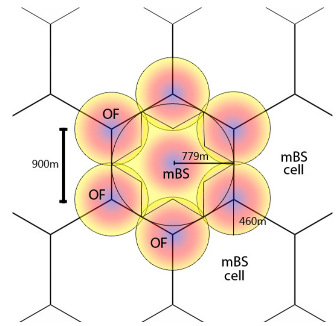

Fig. 1. A single 6 OF femto-bordered macrocell with an outer radius of 900m.

It should be noted that this strategy, also impacts the level of cooling and other expensive energy consumptions of the mBS, however not to that same extent as on the PA. Furthermore, since this strategy relies on the macrocells' borders, it is dependent on the current layout of the macrocell grid and therefore requires each targeted macrocell to be *entirely* surrounded by OFs.

2.1.1 Calculations

Formulas and their usage:

In these calculations the cell power-efficiency will be inspected by comparing a single macrocell's power consumption to a femto-bordered version of the same cell. The suburban version of the Empirical COST-Walfisch-Ikegami model (Non Line-of-Sight) [14] will be used for calculating the path losses since it is widely accepted. An OF height of 14.6 meters will be assumed. The rest of the assumptions are listed in Table 1.

TABLE 1
Parameters and Assumptions

Equipment	
OF P_{Tx}	20 dBm [8]
OF antenna gain	10 dBm [8]
P_{OF} (power cons.)	14.5 w [8]
mBS height	14.6 m
mBS P_{Tx}	35 dBm
Receiver height	1.5 m
Channel frequency	2 GHz
Technology	UMTS
Environment (*Suburban*)	
Mean bldg. height	7 m (2-3 storey buildings)
Mean street width	20m
Mean bldg. separation	4m
Road orientation angle	55° (worst case)
Maximum Path losses	
OF	128.86 dB [15]
mBS	141.9 dB [15]

In order to determine how much energy will be saved with this strategy in place, the new required coverage area of the relieved macro base station (denoted further on as mBS_r) must be calculated. The maximum acceptable distances for an OF and a mBS with the given assumptions and path loss model are approximately 460 m and 1010 m respectively. For this reason, the mBS_r only needs to reach a distance of 779 m to prevent coverage gaps as depicted in Fig. 1.

To determine the power consumption of the mBS_r its transmission power (P_{Tx_r}) must be calculated. The P_{Tx_r} can be calculated by adjusting the result of a standard UMTS link budget [15]. The following is the formula (valid only in this scenario) used to find the P_{Tx_r}:

$$P_{Tx_r} = L_x - \left(L_o - P_{Tx_o}\right) \qquad L_o > L_x \qquad (1)$$

where,

P_{Tx_r} = Required Tx power for the mBS

L_o = Maximum path loss for a mBS in the given environment

P_{Tx_o}= The mBS's Tx power used to calculate the L_o

L_x = The new maximum path loss desired

L_x of 137.5 dB gives the distance of 779 m according to the path loss model.

Therefore, the needed P_{Tx_r} for the relieved mBS would be:

$$P_{Tx_r} = 137.5\, dB - (159.86\, dB - 43\, dBm) = 20.64\, dB$$

Now the power consumptions of the mBS before and after placing OFs on its borders can be calculated as follows.

Let 'mBS' be a regular macro base station *without* OFs and '$mBSf$' be *with* OFs.

The power consumption of a base station can be calculated by the formula: [16]

$$P_{BS} = N_{sector} \cdot N_{PApSec} \cdot \left(\frac{P_{tx}}{\mu_{PA}} + P_{SP}\right) \cdot (1 + C_c) \cdot (1 + C_{PSBB}) \qquad (2)$$

where,

N_{sector} = # sectors

P_{Tx} = Tx power

N_{PApSec} = # PAs per sector

μ_{PA} = PA efficiency

P_{SP} = Signal processing overhead

C_{PSBB} = Battery backup and power supply loss

C_c = Cooling loss

$$P_{mBS} = 3 \cdot 1 \cdot \left(\frac{35}{.15} + 58\right) \cdot (1 + .29) \cdot (1 + .11) = 1251.48\ watts$$

$$P_{mBSf} = 3 \cdot 1 \cdot \left(\frac{20.64}{.15} + 38.2\right) \cdot (1 + .29) \cdot (1 + .11) = 755.18\ watts$$

The difference between the S 's range (1010 m) and the $mBSf$'s required range (779 m) is the direct result of the OF's influence in coverage area. The power efficiency obtained by segmenting the S 's borders can be calculated by a ratio of power consumption before and after the change. The formula must also take into account the fact that each of the six OFs overlap three mBSs. This means that only a third of each OF's coverage area is actually used in that particular macrocell. For this reason only a third of each OF's power needs to be considered in the numerator of the ratio. Therefore, the cell power-efficiency of segmenting a macrocell's borders (CPE_B) can be calculated as follows:

$$CPE_B = 1 - \frac{P_{mBSf} + P_{OF} \cdot \left(6 \cdot \frac{1}{3}\right)}{P_{mBS}} \qquad (3)$$

therefore the cell power-efficiency in our case is:

$$CPE_B = 1 - \frac{755.18 + 14.5 \cdot \left(6 \cdot \frac{1}{3}\right)}{1251.48} = 37.34\%$$

Result of the calculations:

The results show significant power savings with this strategy in place. An effective 37.34% of the energy consumed can be saved on a per-cell basis with a distribution dependent on the current mBS layout. It should be noted that if the user density is too high, and 16-64 simultaneous active users per femtocell is insufficient, then there are two options for modifying this strategy. Either more femtocells can be added to the borders or this strategy can be implemented at night when user densities are lower [4]. In both cases this strategy is an effective option for saving energy.

2.2 Femto-Gridding

The strategy is to segment entire macrocells by creating a femtocell grid outdoors. The goal is to relieve mBSs during certain hours or to replace them entirely with lower powered substitutes. Depending on the cell's active user density, it may only be possible to activate such a scheme during the night where there is less of a demand. However, some current OFs can support 16-64 simultaneous calls [9] so the spatial reuse of femto-gridding over a 900 meter radius cell can allow for 112-448 simultaneous active calls. This amount can be more than sufficient for most cells of that size.

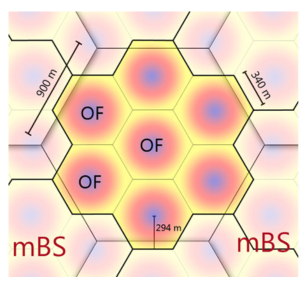

Fig. 2. An independent 7 OF template aligned with 900m outer radius macrocells.

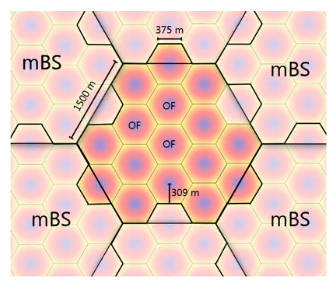

Fig. 3. A dependent 16 OF template over a 1500m outer radius macrocells.

By relieving an entire mBS with several femtocells that consume only a few watts tremendous amounts of energy can be saved on a per-cell basis. This strategy can be deployed over any number of complete macrocells through one of many femto-gridding templates. A femto-gridding template is simply a standard cell cluster of OFs that can be repeated. There are two kinds of templates that this strategy offers which either respect or disrespect the current macrocells' layout; dependent and independent. When a template is dependent it can be tiled in the same manner as the hexagonical macrocells around it. For this reason, it is called dependent since no matter how many tiles of the template have been laid down it will still be aligned exactly with a macrocell. The opposite is true for an independent template; later tiles will not necessarily be aligned with any macrocell.

Fig. 2 depicts an independent 7 OF template and Fig. 3 represents a dependent 16 OF template. Each figure is contrasted to macrocell grid with each macrocell having the same total coverage area as the template's OF cluster.

Although dependent-templates are easier to implement since they fit on the existing macrocell grid, independent-templates broaden the collection of formations providing greater flexibility to extend the limits of the coverage areas of the OFs. Extending the OF's coverage areas can improve the extent of the 'area power-efficiency' by varying amounts. Therefore, the extent of the efficiency of the chosen template is dependent on the macrocell's size and available femtocell technology.

2.2.1 Calculations

Formulas and their usage:

In these calculations the cell power-efficiency will be determined by comparing a single macrocell to a femto-gridded cell with same total coverage area. An independent seven OF template with a macrocell outer radius of 900 meters will be used Fig. 2. Furthermore, the suburban version of the Empirical COST-Walfisch-Ikegami model (Non Line-of-Sight) and the assumptions in Table 1 will be used. This means that the maximum acceptable distance for the mBS in this environment, with the given parameters in Table 1, is approximately 1010 m. Note that the concluding results can be applied to an independent template as well since the calculations consider a power to coverage area ratio which is applicable to both templates. For our calculations we will focus on one mBS as was done in section 2.1.1.

First, with the chosen template, we must determine if the OFs' required coverage radii are feasible in the given environment. In order to do so the assumption is made that the mBS and each of the OFs coverage areas form standard hexagonical cell shapes. The OFs' required outer cell radii can now be determined since a hexagon's outer radius is equivalent to its side length.

The required OF cell side length can be calculated by determining the OF's coverage area. The area of a hexagon can be calculated from the formula

$$A = \frac{3\sqrt{3}}{2} \cdot t^2, \qquad (4)$$

where t is length of its side (equivalent to its outer radius). Since the sum of the OFs' coverage areas match the area of the given macrocell,

$$A_{Macrocell} = A_{OF} \times N_{OF} \quad \Rightarrow \quad A_{OF} = \frac{A_{Macrocell}}{N_{OF}} \qquad (5)$$

where,

A_{OF} = A single OF's cell coverage area

$A_{Macrocell}$ = A single macrocell's coverage area

N_{OF} = The number of OF's in the selected template

From here the side length can be determined in the following way:

$$A_{OF} = \frac{3\sqrt{3}}{2} \cdot {OR_{OF}}^2 = \frac{A_{Macrocell}}{N_{OF}}$$

$$OR_{OF} = \sqrt{\frac{2 \cdot A_{Macrocell}}{3\sqrt{3}(N_{OF})}} = \sqrt{\frac{2\left(\frac{3\sqrt{3}}{2} \cdot {OR_M}^2\right)}{3\sqrt{3}(N_{OF})}} = \sqrt{\frac{{OR_M}^2}{N_{OF}}} \qquad (6)$$

where,

OR_M = Outer radius of the macrocell

$A_{Macrocell}$ = Area of macrocell

OR_{OF} = Outer radius (side length) of each OF

Therefore with the selected template and parameters,

$$OR_{OF} = \sqrt{\frac{{OR_M}^2}{N_{OF}}} = \sqrt{\frac{900^2}{7}} \approx 340\ m.$$

Now the OFs' minimum height can be determined according to the path loss model of the environment. A height of approximately 11.1 meters provides the OFs with a coverage radius of about 363 meters with about 20 meters of overlap for handovers with an acceptable carrier to interference ratio (CIR). These results show that the selected template is feasible in the given environment.

At this point, the cell power-efficiency of segmenting and entire mBS's coverage area with a grid of OFs (CPE_G) can now be calculated from the following formula:

$$CPE_G = 1 - \frac{P_{OF} \cdot N_{OF}}{P_{mBS}} = 1 - \frac{14.5 \cdot 7}{1251.48} = 91.88\% \qquad (7)$$

Result of the calculations:

It is possible that 91.88% of energy consumed by a macrocell can be saved with this strategy. However, it should be noted that the results will vary slightly according to the femto-gridding template chosen. For instance, should the operator desire better spatial reuse in order allow for more active users per cell, the operator may choose a template with a denser distribution of OFs. Doing so will change the results of the cell power-efficiency, but not to a great extent.

2.3 Comparing Technologies

Femtocell technology is a better candidate than the standard technology, found in regular short-range base stations, when used in the proposed strategies. The comparison between using femtocell technology and standard technology in these strategies can be made through an adjustment of the P_{OF} (OF power consumption) in Table 1. In order to find the power consumption of a regular short-range base station, the parameters in table 1 are assumed and (2) is used. Fig. 4 shows that femtocell technology offers better power efficiency in comparison to the usage of standard technology in each of the respective strategies offered.

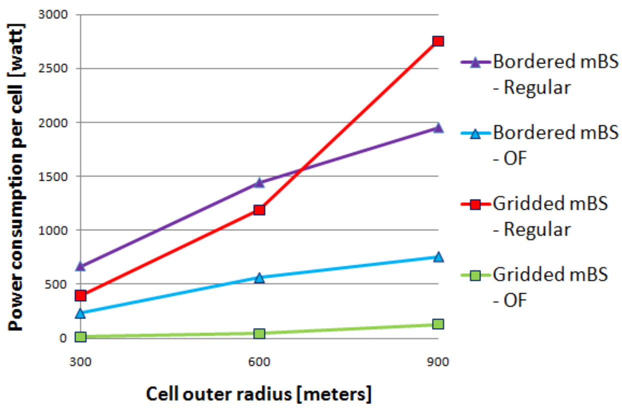

Fig. 4. A comparison of power consumptions between using regular base stations and OFs in each of the two proposed strategies.

3. CONCLUSION

The up and coming issues of the near future are the ICT's energy costs and negative impact on the environment perpetuated by the fast growth of the user data rate demand. However, the vicious cycle of having to install more costly infrastructure to compensate for the high demand while harming the environment even more can be avoided with femtocell technology. It is clear that base stations that use femtocell technology are better 'green' candidates than others when it comes to deterministic outdoor distributions.

Both outdoor femtocell power efficiency strategies outlined in this paper have the potential to save exceptional amounts of energy while satisfying the demand for greater bandwidths. The femto-bordering strategy can save 37.34% of a macrocell's energy consumption on a per-cell basis. It is clear that this strategy should be used if the mBS cannot be completely shut off for a period of time. Otherwise the femto-gridding strategy should be used because of its high energy efficiency of 91.88% and more effective spatial reuse qualities. Compared to a joint picocell and macrocell deployment which can reduce energy consumption by 60% [7] the femto-gridding strategy is far more effective. The femto-gridding strategy can either be implemented only during evenings when the traffic density is lower or throughout the entire day if the spatial reuse fits the demand.

Although the parameters for strategies assessed in this paper were assuming implementation in suburban scenarios, the same strategies are applicable to urban environments as well.

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