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Published in:
Annales des Telecommunications

DOI (link to publication from Publisher):
10.1007/s12243-012-0287-x

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Ann. Telecommun. (2012) 67:133–146
DOI 10.1007/s12243-012-0287-x

Impact of picocells on the capacity and energy efficiency of mobile networks

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Received: 15 December 2010 / Accepted: 18 January 2012 / Published online: 25 February 2012

Abstract The deployment of small cells in mobile networks has aroused a large interest in the last few years. This paper investigates the impact of picocell deployment on the performance and power consumption of mobile networks. Since different network upgrades introduce different performance gains, comparing different configurations exclusively on their overall power consumption can be rather biased. For this reason, a new key performance indicator, termed "energy efficiency", is introduced and used throughout this study, bringing together network performance and its overall power consumption. In the first section of the study, a theoretical analysis for the Erlang-like capacity of a network, considering a uniform topology and traffic, is performed, using queuing theory analysis, namely processor-sharing queues. Results show that in all cases the deployment of picocells improve the performance of the network, however the energy efficiency is noted to be dependent on the deployment scenario considered. In the second part of the study, a more realistic scenario with non-uniform topology and traffic is considered, which is carried out through a large-scale system level simulator. Results show that by deploying picocells in areas experiencing high levels of traffic, the energy efficiency of the network can be considerably improved.

Keywords Mobile networks · Picocells · Energy efficiency · Capacity · Sleep mode

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1 Introduction

Since its first release, 3G wireless technology has come a long way forward. Each new release of 3GPP specifications has introduced a number of new features that offer greater opportunities for both consumers and network operators alike. 3GPP Release 10 specifies LTE-A, which introduces several significant improvements over LTE Release 9 [1]. Examples of these are: relays, carrier aggregation, and Heterogeneous Networks (HetNets). This paper investigates a special aspect of HetNets, which is the deployment of picocells to offload parts of the traffic from the macro layer of the network. Note that, although small cell deployment is a part of the LTE-A standard, it is in no way entirely restricted to LTE-A. In fact, there is a large interest from network operators to assess the impact of small cell deployment on the performance of their HSPA networks, in an attempt to define an optimal deployment strategy for the next couple of years.

A good amount of research has been dedicated to interference management between the macro and pico layers [2]. This has also been often integrated within the framework of Self Organizing Networks [3]. This work focuses on the capacity gains and energy impactions that can be expected from deploying picocells.

The energy efficiency of the radio access networks has become a widely discussed and critical issue for future wireless networks (especially HSPA+, 3G LTE and LTE-

Advanced). Macro base station sites are the most energy-consuming nodes in the access network and are at the heart of every green radio scheme [4, 5]. For this reason, besides the achievable capacity gains, this investigation mainly focuses at the power consumption of the resulting heterogeneous network. The energy efficiency of the network is measured by dividing the traffic capacity with the power consumption, as recommended by [4]. This measure is considered as a KPI for the overall quality of the network.

The subject of picocell deployment is in this study covered from both a theoretical and a practical point of view. At first, we start by considering a uniform deployment within a network with homogeneous traffic. Using queuing theory techniques, the Erlang-like capacity, i.e., the maximum traffic intensity that can be served by the network under a target quality of service (QoS), is calculated. Following this, a real HSPA network topology and traffic distribution are considered for deploying picocells in traffic hotspots. In both cases, energy models for both macro and picocells are used to calculate the power consumption of the network. Results show that in some scenarios, picocells have the potential of increasing the energy efficiency of mobile networks. This is however dependent on the maturity of the equipment and the evolution of the macro layer of the network.

Since the traffic carried by the network varies constantly and considerably over time, a sleep mode feature for the deployed picocells is investigated for both cases. By putting a number of picocells in sleep mode, further energy savings are observed.

2 Related work

An important set of works on green radio have been dedicated to the reduction of the transmitted power of base station sites. The objective is to find the optimal transmission power that ensures sufficient network coverage and capacity (see for instance [6, 7]). The impact of reducing the cell size on the energy performance of a High-Speed Downlink Packet Access (HSDPA) has been investigated in [8]. A reduction of the cell size from R_1 to $R_2 < R_1$ has been shown to increase the power consumption gain of the cellular network by a factor $n=(R_1/R_2)^2$. However, alone, these schemes are not sufficient to reduce the power consumption of wireless networks and a sleep mode is thus necessary for any optimal design of green base stations [9]. A similar study, based on a real network scenario, has shown that by implementing sleep mode during hours with low network traffic, a daily energy saving in the order of 30% is possible [10].

With regards to the deployment of small cells, particular attention has been dedicated to the energy savings of indoor access points [11, 12], where sleep mode mechanisms have been used. Out-of-band low consumption radio modules have been used to awaken femtocells when a call arrives.

For an outdoor environment, small cells, or technically low-power base stations, have been shown to improve the energy efficiency [13]. In this study, the approach is based on a link budget analysis, where the average throughputs, with and without small cells, are compared for different cell ranges and deployment scenarios. Although the obtained results give an interesting insight about outdoor small cell deployment, the dynamic behavior of users and the impact that this has on the user-perceived QoS has not been addressed.

In this paper, we introduce both link budget and flow-level queuing theory analyses. With the main objective being to preserve the QoS of users, capacity, and energy efficiency figures that consider the traffic intensity and the number of active picocells are derived. A network wide sleep mode is also applied, where during low-traffic situations, some of the picocells are shut down. To note that this sleep mode is performed in a semi-static way, meaning that it depends on the average traffic, on an hour-by-hour basis. Putting picocells in sleep mode has no impact whatsoever on the coverage of the network, since these are deployed in dense urban areas for boosting capacity. Within such areas, it is the macro layer of the network that ensures coverage.

The remainder of this paper is organized as follows. We begin, in Section 3, by considering a uniform deployment of picocells and showing how to calculate capacity and energy efficiency. Section 4 extends the study to the case of a non-uniform network topology and illustrates the capacity and energy gains in different scenarios. Section 5 eventually concludes the paper.

3 Analysis of a uniform deployment of picocells

3.1 Throughput calculations

For the analytical calculations proposed in this paper, the downlink of a uniform network configuration is considered. A user equipment (UE) M in the target cell 0 is characterized by a distance R to base station 0 and an angle θ with a reference axis as shown in the Fig. 1. The points at the center of all surrounding cells indicate the interfering evolved node Bs (eNBs). An omni-directional pattern antenna has been considered. The Okumura–Hata propagation model is used for macrocells. For pico-cells, the 3GPP model for outdoor relays is used. For each point of the cell, we derive the signal-to-interference-plus-noise-ratio (SINR) received from the target eNB and the different picocells. The aim is to calculate the throughput of a UE located at this point and that is served by either the macrocell or the picocell. Throughout these calculations, the interference

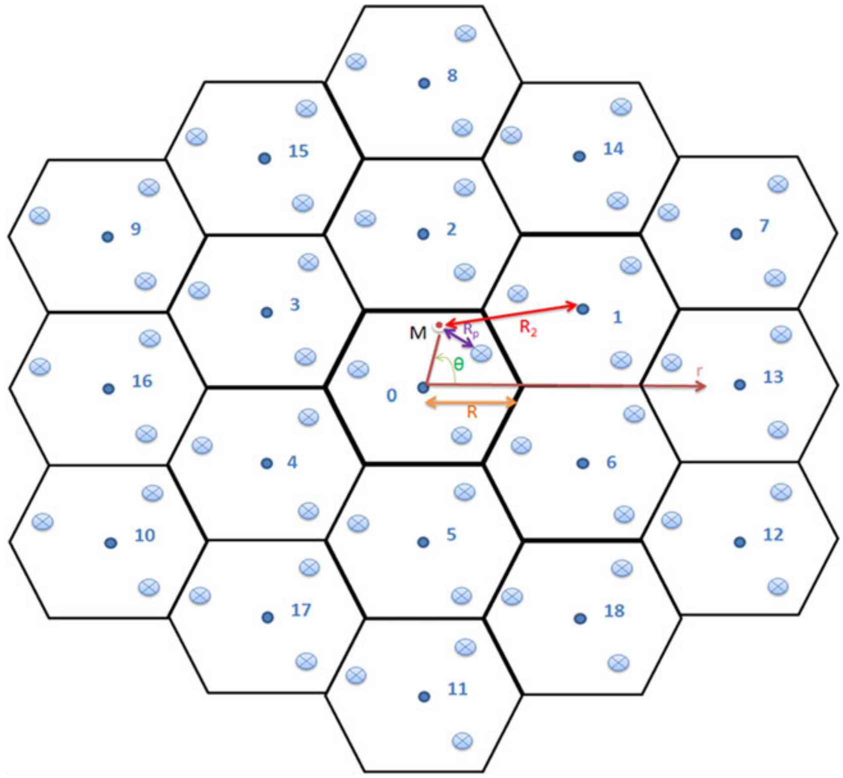

Fig. 1 Network configuration with three picocells per site

generated from surrounding macrocells and picocells is taken into consideration.

For each node i (it being a picocell or macrocell) an average load in the interfering cells equal to χ is assumed. Note that Table 1 contains the variables that are used in this section and their meaning.

3.1.1 LTE

In LTE, χ is the average proportion of occupied resources in the cell. The SINR can thus been calculated for each point of the cell as follows. For LTE, the same formula describes the distribution of the number of collisions at each resource block (RB), be it allocated to a user served by an eNB or a picocell. Recall that an RB is the smallest amount of time-frequency resource that can be allocated to a user in LTE.

Table 1 Variables used in this section and their meaning

P_{max}	Maximum transmission power of the cell
q_0	Path loss between the receiver and the serving node
q_i	Path loss between the receiver and the interfering node
P_{com}	Power of common channels
α	Orthogonality factor
S	Spreading factor
F	Interference factor
N_0	Thermal noise
F	Average file size
λ	Overall arrival rate

We define the vector **X** of zeros and ones whose dimension is equal to the number of neighboring cells and whose elements take the value 1 if there is a collision with the corresponding cell. As for the macro networks studied in [14], the probability distribution of the number of collisions is calculated by:

$$\Pr(\mathbf{X},\chi) = \chi^{\mathbf{X}'\mathbf{X}}(1-\chi)^{1-\mathbf{X}'\mathbf{X}}$$

where $\mathbf{X}^t$ is the transpose of **X**. For a given vector of collisions **X**, the average SINR at each point of the cell, characterized by distance r to the macro eNB and angle θ with a reference axis (as shown in Fig. 1), can be calculated for the two different links. These are the direct link between the eNB and the UE ($\mathrm{SINR}_{\mathrm{eNB\text{-}UE}}$), and the second link between the picocell and the UE ($\mathrm{SINR}_{\mathrm{pico\text{-}UE}}$):

$$\mathrm{SINR}(r,\theta,\chi) = \sum_{\mathbf{X}} \Pr(\mathbf{X},\chi)\frac{P_0/q_0(r,\theta)}{\sum_{i=1}^{n} X_i \frac{P_i}{q_i(r,\theta)} + N_0}$$

where P_{max} is the maximum transmission power of the cell, q_0 is the path loss between the receiver and the serving node, q_i is the path loss between the receiver and the interfering node, and N_0 is the thermal noise.

3.1.2 HSDPA

In HSDPA, χ is the average proportion of cell power that is used for common and data channels. The interference between cells is attenuated by the use of scrambling codes, in which case the SINR can be calculated by:

$$\mathrm{SINR}(r,\theta,\chi) = \frac{S \times P_{\max}}{\alpha P_{\mathrm{com}} + \chi P_{\max} F(r,\theta) + N_0 q_0(r,\theta)}$$

where P_{com} is the power of common channels, α is the orthogonality factor, S is the spreading factor, and F is the interference factor, as calculated in [15].

3.1.3 SINR

The UE will then be connected to the link offering the best quality, leading to the final SINR equation:

$$\mathrm{SINR}(r,\theta,\chi) = \max\left[\mathrm{SINR}_{\mathrm{eNB-UE}}(r,\theta,\chi), \mathrm{SINR}_{\mathrm{pico-UE}}(r,\theta,\chi)\right]$$

Using the derived SINR values, link level curves can be used to obtain the throughput of an RB allocated to a UE in the different points of the cell. An example of these curves is shown in Fig. 2. We obtain, by multiplying this throughput by the number of RBs available for each cell, $K_{\mathrm{tot,i}}$ (i=eNB or picocell), the peak throughput over all the areas covered by node i, assuming that all the resources are allocated to one user.

Let D_c be this throughput, calculated at a given point, c, of the cell and N the number of points in the considered grid.

3.2 Flow-level capacity analysis

In the previous section, the achievable throughput at the different positions within a cell, for a stand-alone user, has been studied through link budget analysis. This is however not sufficient, since in high-traffic situations, several users are scheduled in parallel. Thus, this requires a flow-level capacity analysis, in which users arrive and depart from the cell dynamically.

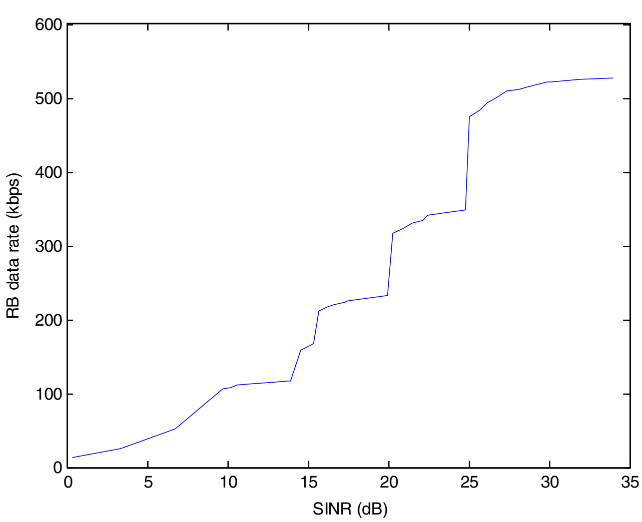

Fig. 2 Downlink LTE link curve

A network carrying elastic traffic and which is composed of only macrocells can be modeled as a processor-sharing queue, and its evolution described by the overall number of users in the cell $n = \sum_{c=1}^{C} n_c$ [16]. The cell load is calculated by $\rho(\lambda)=\lambda F/D$, where F is the average file size, λ is the overall arrival rate and,

$$D = \left(\sum_{c=1}^{C} \frac{\lambda_c}{\lambda D_c}\right)^{-1}$$

is the harmonic mean of the throughput. The probability of having n active users in the cell is given by:

$$\pi(n) = \rho^n(1-\rho)$$

If a target throughput T is sought, it is possible to show that the probability for users in position c, to achieve this throughput is given by:

$$\mathrm{QoS}_c(\lambda) = \sum_{m=1}^{k_c} \pi(m) = 1 - (k_c+1)\rho^{k_c} + k_c \rho^{k_c+1}$$

where $k_c=D_c/T$ is the maximum number of allowed users in the cell such that the throughput of a user in position c is acceptable. The average QoS over the cell is thus:

$$\overline{\mathrm{QoS}}(\lambda) = \sum_{c=1}^{C} \frac{\lambda_c}{\lambda} \mathrm{QoS}_c(\lambda)$$

When picocells are introduced, the cell site is modeled as a network of processor-sharing queues as shown in Fig. 3, where the traffic is divided and served by the available nodes (macrocell or picocell). The traffic at each node is given by the proportion of cell locations whose best server is that node. Let S_{pi} and S_m be the area of surface covered by picocells i *(i=1… k)* and the macrocell. These areas are calculated by the proportion of cell locations covered by each node (macrocell or picocell). The arrival rate λ_{pi} of picocell i is equal to $\lambda_{pi} = \lambda \frac{S_{pi}}{S}$ whereas the arrival rate λ_{m} of macro equals to $\lambda_m = \lambda \frac{S_m}{S}$ with S the area of cell.

3.3 Power consumption of network nodes

Macro base stations Through empirical studies, the power consumption of a base station site is given as a function of the cell load for different configurations (number of sectors, installed baseband processing capacity), as shown in [5]:

$$P_{\mathrm{macro}}(\lambda) = P_p + m(P_{\mathrm{TRX}} + \rho(\lambda)P_{\max}/c)$$

where m is the number of installed sectors, P_p is the power consumption of the processing unit, P_{TRX} is the fixed power consumption of the radio module, $P_{\max}$ is the maximum

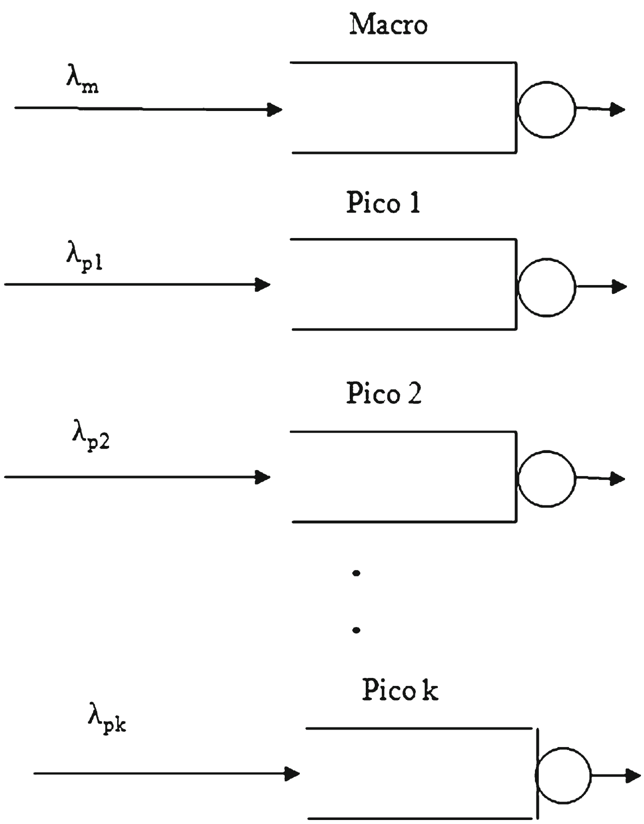

Fig. 3 Queuing model (macrocell with *k* picocells)

output power and *c* is the DC to RF conversion factor. The load ρ is a function of the offered traffic, and is calculated as shown in the previous section. Note that, in multiple-input and multiple-output (MIMO) 2×2 case, each sector will have two transmission chains, so that *m* can be regarded as multiplied by 2. Table 2 presents the set of values that are used to find the power consumption of a macro BTS:

Pico base stations In comparison to macro BTS, picocells operate at much lower transmission power (1 watt). The energy model above shows that the power consumption of a BTS is only lightly correlated to the load. This means that in a picocell that is transmitting little power, the variation in power consumption with load will have an insignificant impact on the overall consumption of the network. As a result, picocells are assigned a fixed power consumption. In order to study the sensitivity of the results, the power consumption (P_{pico}) is varied from 10 to 70 W. Actual consumption figures of picocells are believed to be in the region of 60–70 W; however, this is likely to decrease as the efficiency of the equipments is improved.

Table 2 BTS model parameters

P_p	110 W
P_{TRX}	100 W
$P_{\max}$	40 W
c	0.32

Considering the macro together with the *K*-deployed picocells, the power consumption of a network node is given by:

$$P_{\text{cell}}(\lambda) = P_{\text{macro}}(\lambda) + K \cdot P_{\text{pico}}$$

An additional term, energy efficiency, is introduced to put into perspective the power consumption of the network with the ability of the network to carry traffic. This is defined as the ratio between the capacity of the network and the power consumption, and is expressed in capacity per watt per unit surface. Note that the term "capacity" has to be precisely defined. From an operator point of view, the capacity is the maximal amount of traffic that can be served by the network, under a target QoS. This is expressed by:

$$C = \lambda_{\max}; \quad \overline{\text{QoS}}(\lambda_{\max}) = \text{QoS}_{\text{target}}$$

Note that the energy efficiency is generally expressed by a volume of data per kilowatt hour (megabit per kilowatt hour). However, since we calculate cell capacity in volume per unit time (kilobits per second), the energy efficiency is simply the capacity divided by the power (1 Kbps/W= 3600×Mbit/KWh).

3.4 Sleep mode application

When dimensioning a mobile communications network, the busy hour traffic is taken as a reference to calculate the required network capacity and the number of base station sites needed. However, such high volumes of traffic can only be observed for about 2 to 3 h a day. For this reason, a sleep mode mechanism that shuts down capacity enhancing sites when traffic is below a certain threshold can be used to improve the energy efficiency of the network. In this study, sleep mode is only allowed for the deployed picocells.

Assuming that the requested QoS is ensured, in the event that one or more picocells, within a particular macrocell, are not utilized (too much network capacity for requested traffic volume), then these picocells are shut down, reducing the overall power consumption. If *k* picocells, among the *K* existing ones, are shut down, the power consumption is given by:

$$P_{\text{cell}} = P_{\text{macro}} + (K - k)P_{\text{pico}}$$

3.5 Results

In order to evaluate the impact of picocell deployment and sleep mode on the power consumption and QoS of the network, some numerical results are hereby presented. An

LTE-A network in a dense urban area, with an inter-site distance of 800 m, is assumed. The transmission power for picocells is set to 30 dBm (1 watt). These are deployed close to the cell edge, at 450 m from the macro eNB.

In order to compare the impact that a different number of picocells have, four deployment strategies are considered:

- Macro only: no picocells are deployed.
- Light-pico: deploying three picocells/sites (one picocell per cell).
- Medium-pico: deploying six picocells/sites (two picocells per cell).
- High-pico: deploying nine picocells/sites (three picocells per cell).

In Fig. 4, we plot the cell outage rate, i.e., the probability that the achievable user throughput is less than the target 500 Kbps. For all four deployment scenarios, the traffic is increased from 10 to 25Mbps/cell. The term outage rate can be considered as being inversely proportional to the QoS. From this figure, if a target outage rate of 5% (or less) is sought, the Erlang-like capacity can be derived (first line of Table 3).

With regard to the power consumption shown in Fig. 5, as expected this is noted to increase when additional picocells are deployed in the network. From Figs. 4 and 5, we can obtain the power consumption corresponding to the maximum capacity that the network can carry (second line of Table 3). Note that, even if the power consumption of the network increases, the deployment of picocells is necessary and is driven by the need to boost network capacity in order to accommodate the increase in traffic.

As previously mentioned, the energy efficiency is measured in capacity per watt per unit surface. Since a constant inter-site distance for macrocells is considered, the energy efficiency can be measured in kilobit per second per watt cell. Table 4 compares the energy efficiency for the four previously described strategies for different values of P_{pico}. As expected, the energy efficiency is inversely proportional to the picocell power consumption. When compared to the macro-only case, a dense picocell deployment is more energy efficient for P_{pico} less than 30 W. The table also shows that by having picocells with lower power consumption, the same energy efficiency can be achieved with fewer picocells.

Table 3 Capacity and power consumption of different strategies with P_{pico}=30 W

	Macro only	3 picocells	6 picocells	9 picocells
Capacity (Mbps/cell)	15	16	17	19.5
Power (W/cell)	352.66	384.6	414.74	446.67

To investigate the impact on the performance of introducing sleep mode in picocells, the traffic of a typical cell over a 24-h period (Fig. 6) is simulated. While in a typical cell, the volume of traffic varies over time, with a peak observed during the busy hour, traffic is noted to decrease considerably during night time hours.

Figure 7 shows the number of picocells that are needed during each hour of the day for ensuring the same target QoS. This number is calculated as follows:

– For each traffic intensity (each hour of the day, denoted *t*), the QoS is analyzed following the above described model, when there are *x* active picocells, with *x*=3, 6, and 9. Let *QoS(t, x)* is the QoS when there are *x* active picocells, at time *t=0,…, 23*.

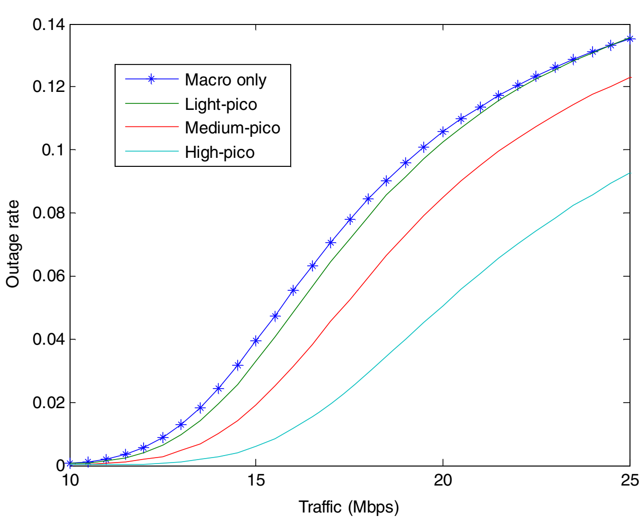

Fig. 4 Cell outage rate (P_{pico}=30 W)

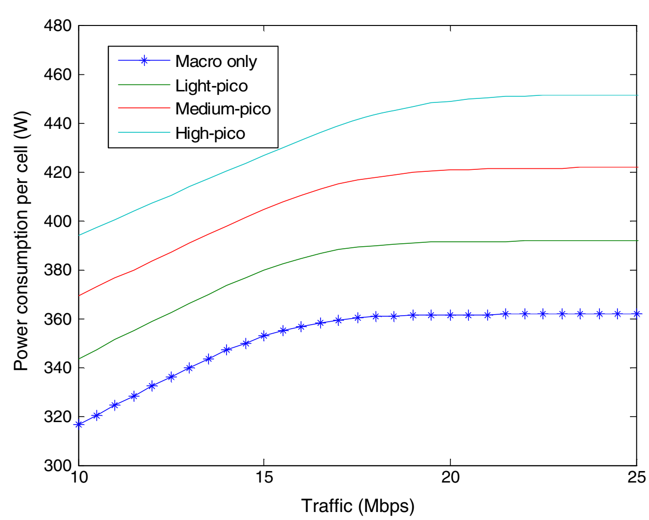

Fig. 5 Power consumption in the cell (P_{pico}=30 W)

Table 4 Energy efficiency (kilobits per second per watt per cell) with different values of P_{pico}

	P_{pico}						
	10 W	20 W	30 W	40 W	50 W	60 W	70 W
Macro only	43.5	43.5	43.5	43.5	43.5	43.5	43.5
3 picocells	44	43	42	40.5	39.5	38.5	38
6 picocells	45.5	43.5	41	39.5	37.5	36	34.5
9 picocells	50.5	47	44	41	38.5	36.5	34.5

– The optimal number of picocells, for each hour of the day, is then setup so that the minimal QoS is satisfied:

$$\bar{x}(t) = \arg\ in\mathrm{QoS}(t, x)$$
$$\text{Subject to}: \mathrm{QoS}(t, x) \geq \mathrm{QoS}_{\mathrm{target}}$$

It is observed that the maximum number (9) of picocells, are only required at the busy hours (from 5pm to 6pm hours and from 2000 hours to midnight). However, in hours with medium to low traffic three, six, or even at times zero picocells are needed. Figure 8 shows the power consumption of the cell area coverage (picocell+macrocell) with and without sleep mode corresponding to the traffic profile in Fig. 6. The average energy efficiencies obtained for the two schemes are: 45 Kbps/W/cell for the case without sleep mode and 52 Kbps/W/cell for the case with sleep mode. This corresponds to an increase in energy efficiency of 16%.

4 Non-uniform traffic case

In reality, base station sites of actual mobile networks are organized in an irregular (but yet planned) topology, with sites being individually positioned and oriented. The traffic

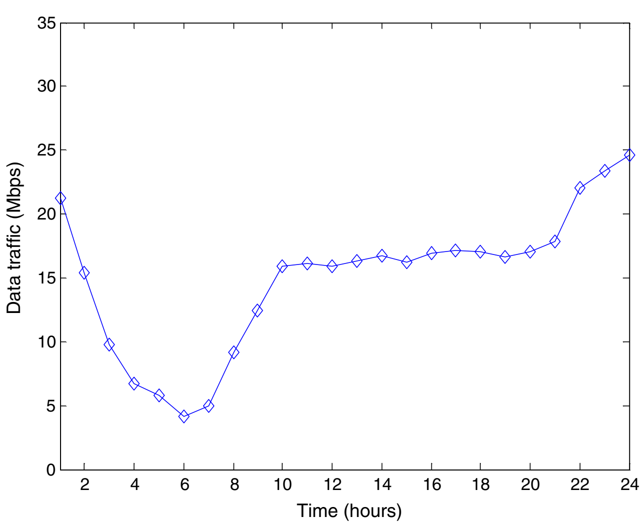

Fig. 6 Average offered data traffic over the day

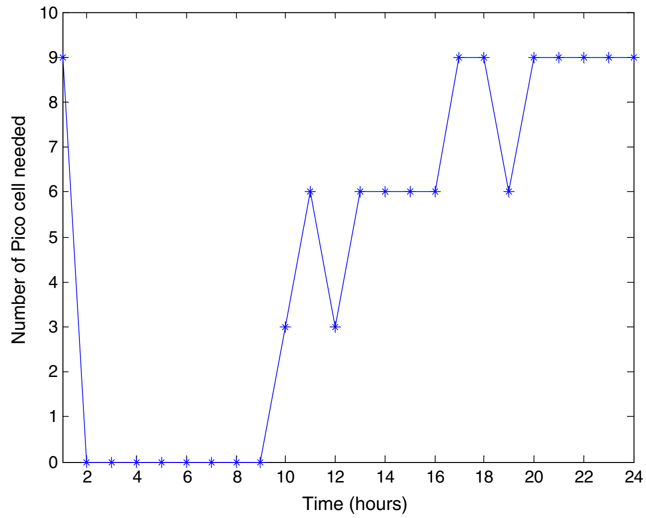

Fig. 7 Number of needed picocells over the day

carried by each cell varies considerably over time, and for a specific moment in time, the traffic within one cell is likely to be different from that of a neighboring cell. Due to such issues, a simple link budget analysis is not sufficient to fully understand the implications that the deployment of picocells could have within a real mobile network. Because of this, in addition to the previously presented theoretical analysis, detailed network simulations based on a real HSPA network have also been carried out. In existing HSPA networks, the deployment of picocells is not the only option for boosting capacity. Other options include: the upgrade of existing sites to HSPA+, the deployment of new macro sites (site densification), the installation of additional HSPA carriers, and the upgrade of selected sites to six sectors. For this reason, the impact of picocells on the power consumption and efficiency is also compared with a small selection of the above capacity enhancing options.

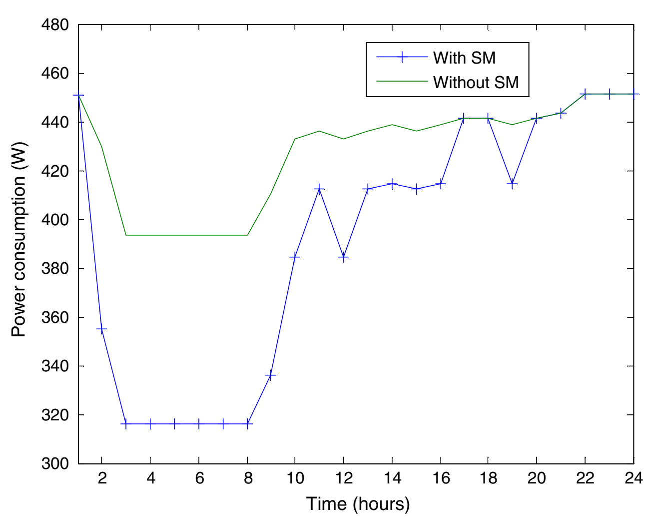

Fig. 8 Power consumption over the day, for nine picocell sites, with, and without sleep mode

4.1 Network simulator description

An irregular network composed of 245 cells (about 85 sites), representing an urban area, representing an actual network, is used as a scenario basis for all of the following simulations. In the beginning, all available sites are assumed to have a single carrier, and be HSPA enabled. Statistics for the various performance results are extracted from a central area of the network, allowing for a "ring" of sites to provide interference, avoiding any edge effects. Being an irregular network, the inter-site distance (ISD) between the various base station sites varies. Figure 9 shows three distribution curves of how the distance between different neighboring sites changes. For this particular network, the average ISD is in the order of 300 m.

The simulation tool used in the investigations is a static network simulator. Based on the Okumura–Hata model, the path loss from every base station to every user is calculated. Since most data traffic originates indoors, all users are considered as indoor users, applying a further 12-dB penetration loss onto the path loss. By knowing the transmission power of every site, the signal-to-interference-plus-noise-ratio (SINR) is then calculated. SINR values are then mapped to data rate through link level data presented in Fig. 10. For cases with multiple users within a cell, resources are appropriately shared to try and ensure that all users get at least their minimum requested data rate. This is presented in further detail below.

4.2 Traffic management

Traffic is simulated by adding a number of active users, all requesting the same minimum data rate, within the network. The location of where users are placed is based on a traffic density map, which is generated based on actual traffic statistics for the same network. Simulations are carried out over a number of years (one simulation representing a single year), with the number of active users added on a year by year basis to represent increasing traffic demand. Over the 8-year period investigated, traffic is increased based on a prediction model, which increases the penetration rate of mobile broadband along an s-shaped curve. Besides the number of active users, traffic is also increased on a per user basis. During the first 2 years of the evolution period, a minimum data rate of 256 kbps is requested by every active user. As per 2012 onwards, this is doubled to a minimum of 512 kbps.

In order to investigate the evolution of the network, and its ability to carry the expected traffic growth, traffic volumes and distributions representing the busy hour are considered. In addition to this, the ability of the network to carry the expected traffic during hours of low traffic is also considered. The traffic profile used is the same as in Fig. 6, and a new traffic density map is generated for this low traffic case. This low traffic case is also used to investigate the possibility of further power savings by enabling sleep mode for picocells during hours of low traffic.

A dense urban area traffic model is used for identifying the number of users that are to be simulated within the network. For the year 2010, the number of active users obtained from the model is compared and verified against the actual traffic statistics available for the real network being used. Table 5 presents an overview of how the number of users for the year 2010 is derived. The penetration rate of mobile broadband users is assumed to increase from a current value of about 15% up to a maximum of 60%, which is reached in the year 2017.

When more than one user is present within a cell, available resources need to be appropriately shared. In the simulation tool used, user scheduling is performed in the following way: All users within a specific cell are sorted according to their SINR. Available resources (codes) to

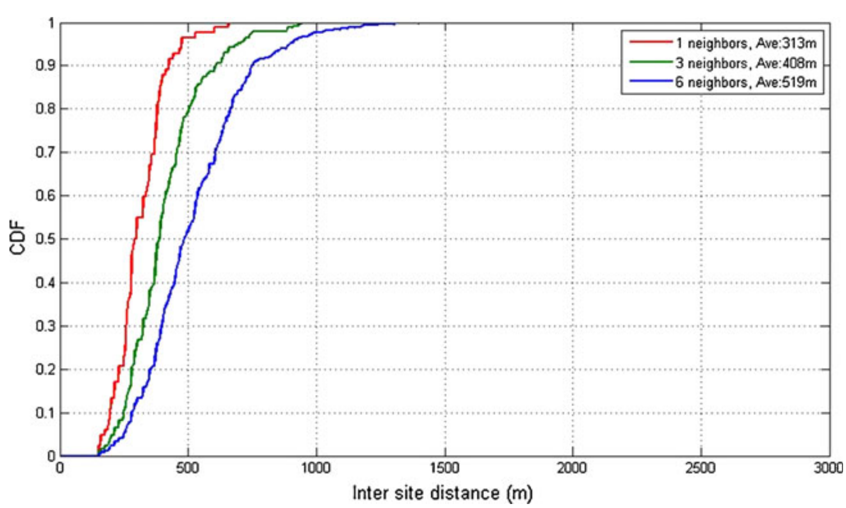

Fig. 9 Statistics about the average inter-site distance between the base station sites being used within the case study area. Different *curves* indicate the number of neighbors considered (the network is not uniform, so that the distances between a base station and its direct neighbors are not equal)

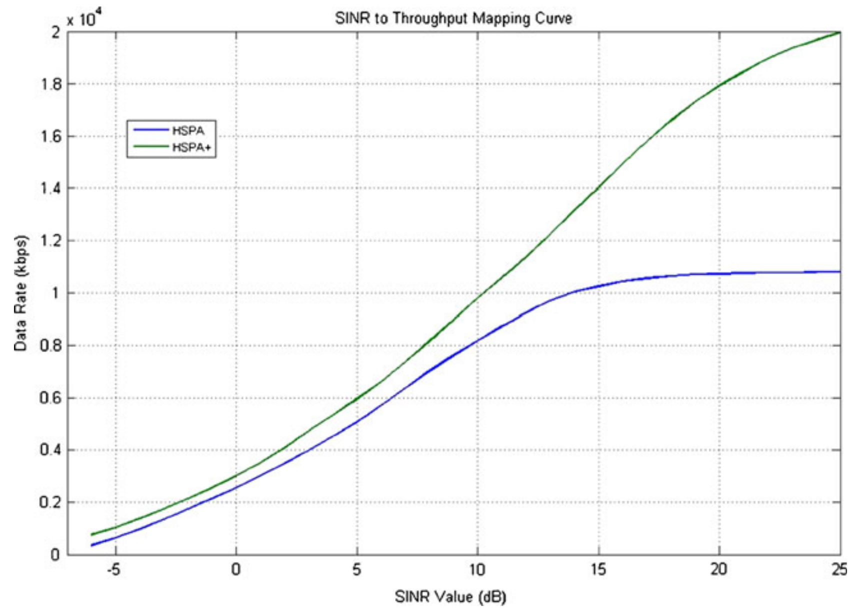

Fig. 10 SINR to Throughput Mapping Curves (HSPA+refers to having MIMO)

guarantee their minimum data rate requirements are first allocated to the users with the high SINR values, thus requiring the least amount of resources. If possible, all users are first allocated enough resources to meet their minimum requested data rate. After that, any remaining resources are shared in a round robin fashion amongst all users. This represents a full load situation, something which is also assumed in the energy calculations.

As previously described, the traffic distribution maps used are based on the traffic statistics for the network being considered. During the simulations, these maps affect the probability of users being placed in a specific cell. The position of these users within that cell is uniformly distributed. Having a map for different traffic categories is expected to give a better understanding about the impact that a reduction in network traffic and a variation in traffic distribution has on the power consumption and energy efficiency of the network. This is also used for investigating the case of picocell sleep mode. The illustration in Fig. 11 shows an example of a traffic distribution map.

Table 5 A table showing how publicly available data of a dense urban area can be used to estimate the number of concurrent active mobile broadband users within a network. Data for the operator share and mobile penetration rate were collected from publicly available sources

Traffic forecast		
Dense urban area scenario		
Population density	6,000	per km^2
Network study area	17	km^2
Population in study area	105,000	
Mobile subscription penetration rate	95%	(4,938 users)
Operator share	33%	
Mobile subscribers in study area	32,918	
Mobile broadband penetration rate in 2010	15%	
Assuming an activity factor	5%	
Number of active users	247	

4.3 Network evolution scenarios

When the existing configuration of the network is not capable of delivering the requested traffic, if possible, heavily loaded sites are upgraded to the next available level. The first upgrade assumed for macro sites is the addition of a second and/or third carrier. This is the easiest and cheapest (assuming operator already holds spectrum license) way of upgrading the network capacity. In the simulations with three carriers, adjacent 5 MHz bands are assigned. The frequency bands can be grouped such that in the event that both or all three carriers are enabled, dual-cell can be supported. This means that the base station site can schedule a single user concurrently on multiple carriers.

The deployment of picocells is implemented by specifying the number of cells that are to be deployed for a specific year. This is always carried out before any additional macro upgrades. Selection of where to deploy new picocells is based upon a weighted factor, which can be set to prioritize between traffic density and coverage (SINR). For this specific investigation, the weights are selected to prioritize areas with high-traffic density and offload surrounding macro sites. If after deploying the new picocells the overall performance of the network is still below the required level, available macro upgrades are carried out to provide the additional capacity required. The investigated area is noted to have four cells that carry relatively higher volumes of traffic that the rest. It is thus assumed that most of the new picocells are to be deployed in these cells. In order to remain

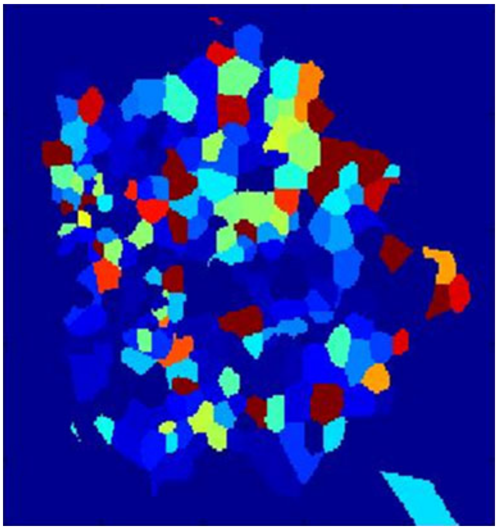

Fig. 11 A traffic distribution map. The cell coverage area for each site is assigned through simulations based only on the pilot power. This is used to determine the SINR in all pixels and assigning a serving base station for any users in that pixel. Cell serving areas are depicted by a color map

in line with the previous investigation a number of picocell deployment scenarios are considered:

- Macro-only upgrades—no picocells deployed.
- Light deployment of picocells (pico-low)—deploying four picocells per evolution year.
- Medium deployment of picocells (pico-medium)—deploying eight picocells per evolution year.
- Dense deployment of picocells (pico-high)—deploying 12 picocells per evolution year.

4.4 Simulation results

4.4.1 Performance of the network

The main parameter defining the performance of the network is percentage of users that are in outage, i.e., that do not achieve their minimum requested data rate. The requested target value is 5%, which has a tolerance band around to allow for the various algorithms to converge. These tolerance bands are marked in Fig. 12 with dotted red lines, with the upper bound (7%) being the one to stay below. The fluctuations within this and other similar figures come as a result of various capacity boosts introduced by the various upgrades.

When comparing the different scenarios being considered, it is noticed that the available macro upgrades alone, are not sufficient to sustain the growth in traffic. This is noted in the years 2016 and 2017 when the percentage of users in outage goes up to 7.4% and 9.8%., respectively. On the other hand, the introduction of picocells is noted to ensure that the percentage of users in outage remains below the required threshold.

With regards to the average achievable data rate per user, it is noted that on average, this is about four times higher than the minimum requested data rate. Since the evolution and upgrade of the network are carried out following the same requirements, it is noted that different options give similar performance results when considering average user data rates.

4.4.2 Upgrade of the network

The introduction of picocells is expected to off-load neighboring macro sites, reducing the extent or need for their upgrade. Figure 13 shows the extent of required upgrades in the network for the four different cases in the year 2017. It is clear that the more picocells are deployed, the less macro site upgrades are required. Already by deploying a few picocells, the need for deploying MIMO is avoided. Additional picocells also eliminated the need to use a third carrier.

4.4.3 Network power consumption

By assuming the same energy models previously used, it takes about 26 picocells (at 70 W per picocell) to consume

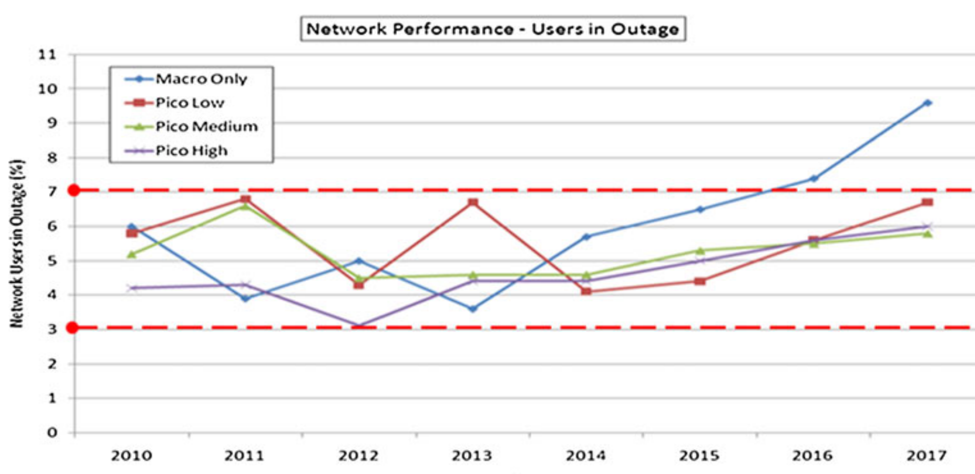

Fig. 12 Network performance in terms of percentage of users in outage, highlighting the target acceptable areas

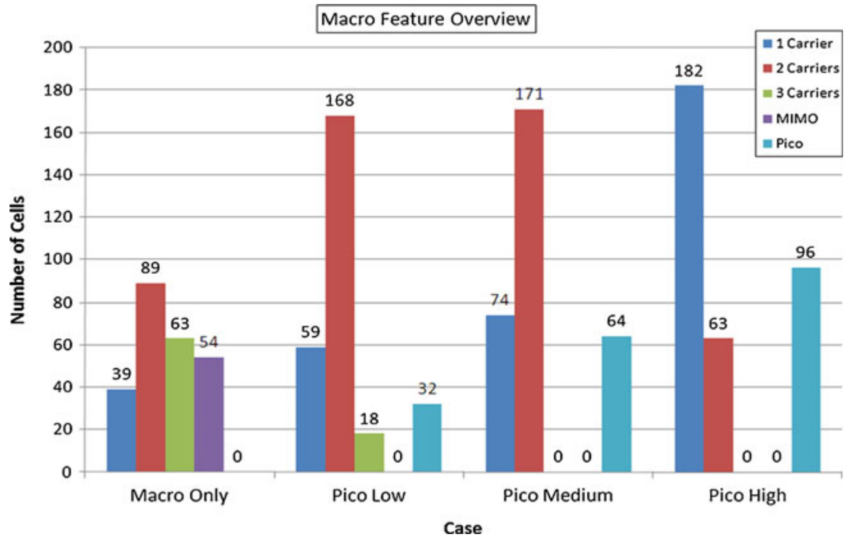

Fig. 13 This figure shows the state of the network at the year 2017. The different *columns* show the extent to which the sites are upgraded

the same power that a three-carrier site with MIMO would. This clearly indicates that reducing the number of macro upgrades should reduce the overall power consumption of the network. Results show (Fig. 14) that the power consumption of the macro-only case and that of the pico-low and pico-medium are comparable only up until 2014. Following that, the introduction of MIMO, boosts up the power consumption. This leaves all pico cases consuming less power. For all pico cases, the first 2 years, show a slight increase in power consumption when compared to macro-only case. This occurs since in the macro-only case no upgrades are carried out in these years.

From 2012 onwards, the pico-high case is noted to have a more positive impact on the overall power consumption of the network, showing a reduction of 30% in comparison to the macro-only case (for the year 2017). The pico-low and pico-medium cases perform similarly showing a reduction in power consumption during 2017 of about 25%. If considered over a 5-year period, when most of the macro upgrades are carried out the reduction in power consumption is averaged to 17% for the pico-high case, and 10% for the other two pico cases.

4.4.4 Network energy efficiency

In order to bring together the performance of the network together with the power consumption, this investigation also considers the energy efficiency of the network. This is measured in kilobits per second per watt and measures the traffic that the network (kilobits per second) can carry per unit of power (watt). Results, presented in the Fig. 15 show that throughout the evolution period, the energy efficiency of the network increases from an average of 8 Kbps/W up to an average of about 25 Kbps/W, irrespective of what

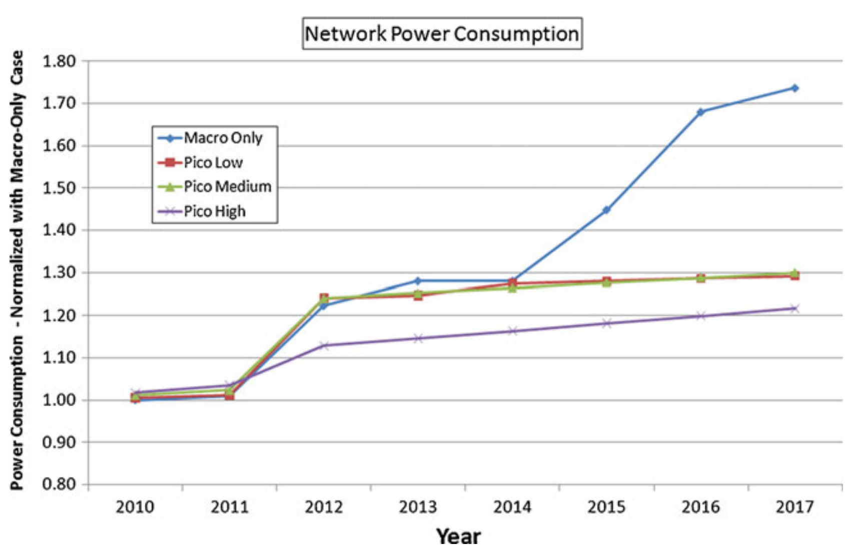

Fig. 14 This figure shows the power consumption of the network over the evolution period. The reference used is the power consumption of the macro-only network of the year 2010

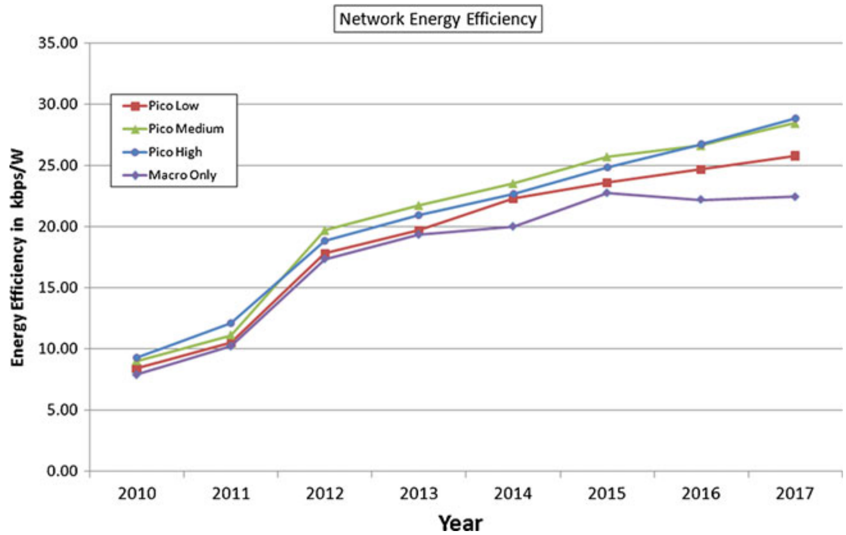

Fig. 15 The energy efficiency of the network in kilobits per second per watt throughout the evolution of the network for the different upgrade options

upgrade is used. This overall increase in efficiency comes from the fact that necessary network upgrades are carried out in the areas with high traffic, so the increase in capacity overcomes the increase in power consumption. While overall, the differences between the various cases are not so drastic, by comparison it is noted that the macro-only upgrade performs worse throughout the evolution. The pico-medium and pico-high, which are the cases performing best with similar energy efficiency figures, give an average gain in energy efficiency of 15.5%.

4.4.5 Picocell power consumption sensitivity

In order to investigate the sensitivity of the above results with the power consumption value being used for picocells (70 W), different values are also considered (50 and 100 W). As noted in the previous section, an increase in power consumption for picocells brings a reduction in the achievable power consumption gains. Nonetheless, when compared to the macro-only case, which is evolved by a number of macro upgrades, it becomes clear that the deployment of picocells is more power effective, even in the case when a massive 200 W per picocell is assumed. It is estimated that for that number of picocells, each would require to consume about 325 W for it to completely cancel the gain in power consumption (Fig. 16).

4.4.6 Picocell sleep mode

Since traffic distribution of a mobile network varies continuously, during hours of low traffic, picocells deployed to help the macro layer during busy hours could now fall in areas with little or no traffic. For this reason, the impact of this shift in traffic distribution has been investigated on the

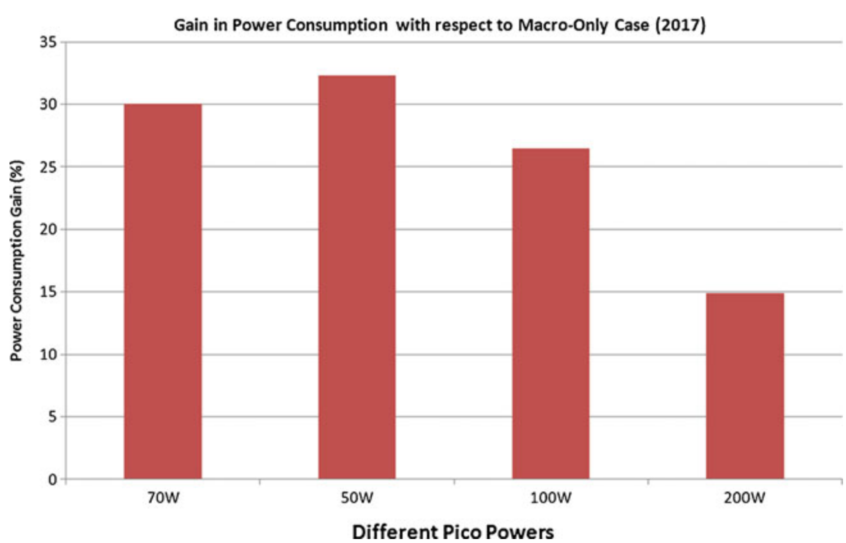

Fig. 16 Sensitivity analysis showing the impact on the power consumption gain for different pico power consumption values

performance and energy efficiency in low traffic cases. In addition to this, since the network is noted to easily cope with low traffic conditions, the sleep mode mechanism previously presented was also implemented. In this case however, since hours corresponding to the lowest traffic are considered, all picocells are put into sleep mode. Note that even if all picocells are shut down, the configuration of the network for the three pico deployment strategies is different, as the macro sites are upgraded differently, as shown in Fig. 13.

Macro-only networks with HSPA+upgrades and no sleep mode are shown to give the best outage level (only 1.5% of users in outage). However, when compared to the same network during busy hour, the energy efficiency of the network falls by 37% (high capacity upgraded sites are carrying far less traffic). With regards to the pico cases, it is noted that the pico-high case performs the worst with an average outage level of 6.8%. Since during the investigated timeframe all picocells are put into sleep mode, most of the network's capacity is inaccessible, which given the traffic, results in an increase in the outage level. The impact on network performance can be noted in Fig. 17.

For the pico-low and pico-medium cases, which produced outage levels within the acceptable region, it is noted that putting picocells in sleep mode had minimal impact on the overall power consumption, with the average gain being less than 5% (picocells consume much less than macro sites, so impact is minimized). It also becomes clear that during hours of low traffic, even if the deployed pico sites are put into sleep mode, the energy efficiency of the network is much lower than that during the busy hour. By considering all investigated cases, the energy efficiency of the network is noted to fall by an average of 48%. In the macro-only case, this is even worse, and is a result based on the fact that base station sites are not efficient during low load conditions. This means that for much less traffic carried, a base station site still consumes high levels of power, reducing the energy efficiency.

5 Conclusion

In this paper, the impact of picocell deployment on the performance (network capacity, power consumption, and energy efficiency) of mobile networks has been studied for different deployment scenarios. A first analysis is performed for uniform topologies and homogeneous traffic, which is based on link budget and queuing theory methods, to show the gain in network capacity. However, the energy efficiency is improved only when the consumption of picocells is very low.

A simulation-based study on a real mobile network, with non-uniform and non-homogeneous traffic, is also carried out. This shows energy efficiency gains in the order of 30%. The reason for this difference is that in a non-uniform traffic case, picocells are deployed in hot-spots of large traffic, thus off-loading neighboring macrocells. This also reduces the need for alternative macro upgrades, which are more power hungry than picocells. On the other hand, in the uniform traffic case, when traffic is high, it is high everywhere and a large number of picocells have to be deployed everywhere in the network, thus increasing the power consumption.

In order to further reduce the power consumption, the impact of semi-static sleep mode in picocells was investigated. Results have shown that based on the scenario, this can lead to both a reduction in power consumption and an increase in energy efficiency. With regards to future works, distributed sleep mode techniques that enable activating/deactivating picocells in a dynamic way, following traffic fluctuations, will be investigated.

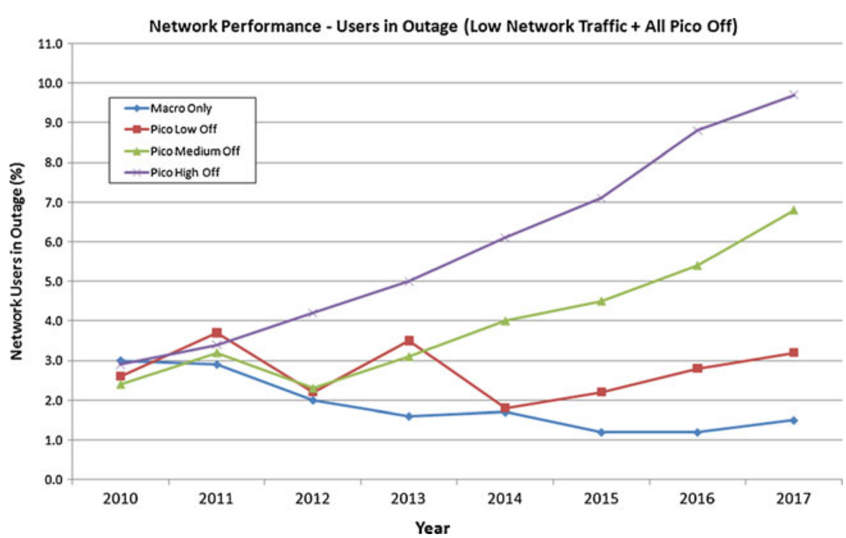

Fig. 17 Effect on the performance (percentage of users in outage) of the network as a result of putting all picocells in sleep mode during low traffic conditions

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