SLEEP Mode Techniques for Small Cell Deployments

Imran Ashraf, Federico Boccardi, and Lester Ho, Alcatel-Lucent

ABSTRACT

Big things come in small packages; a particularly apt description of small cell deployment in cellular networks. *Small* cells have a *big* role to play in orchestrating a cellular network that can overcome the explosive mobile traffic upsurge at little cost to the network operator. However, if left unchecked, a large-scale small cell deployment can substantially increase the network energy consumption with strong ecological and economic implications. In this article, we introduce energy-efficient SLEEP mode algorithms for small cell base stations in a bid to reduce cellular networks' power consumption. The designed algorithms allow the hardware components in the BS to be astutely switched off in idle conditions, such that the energy consumption is modulated over the variations in traffic load. Three different strategies for algorithm control are discussed, relying on small cell driven, core network driven, and user equipment driven approaches. Based on a mixed voice and data traffic model, the algorithms present energy saving opportunities of approximately 10–60 percent in the network with respect to no SLEEP mode activation in small cells, coupled with additional capacity incentives.

INTRODUCTION

Faced with the exponential increase in data traffic, the cellular network operator is confronted with a precarious situation: accommodate the ever increasing traffic growth, yet reduce the costs and consequently increase average revenue per user (ARPU). With the electricity bill contributing to 20–30 percent of the network operational expense, the situation does not get any less intricate with the escalating energy costs. From another (ecological) perspective, there are concerns about the carbon footprint of the information and communication technology (ICT) industry as a whole. Although the global ICT industry accounts for a relatively meagre figure of 2 percent of the global CO_2 emissions, it is expected to increase as other industries begin to utilize communication networks hand over fist to reduce their own carbon footprints. To this end, cellular networks take center stage in reducing global ICT emissions, albeit at the expense of a subtle interplay between improving revenues, reducing costs, and enabling breakthrough services.

The procurement of new data services maps to the provision of higher data rates over the air; therein "small cells" enter the picture. Fueled by the needs of high data throughputs and improved coverage for home and office use, small cells (e.g., femtocell base stations [BSs]) have attracted significant interest in the wireless industry. Residential and enterprise small cell BSs provide great leeway to network operators to leverage on their excellent indoor performance, and offer value-added services and applications to end users. The upshot is a win-win situation: a higher satisfaction quotient from the subscribers' standpoint, whereas the network operator benefits from capital expenditure (CAPEX) reduction, macrocell traffic offloading, and increased revenues [1]. A further knock-on benefit of small cells is their potential to significantly reduce the network energy consumption if integrated with advanced energy saving techniques [2], a topic that forms the core of this article. In this work, we highlight the energy consumption behavior of small cell deployments in cellular networks with emphasis on devising specialized SLEEP mode solutions for small cell BSs that can yield considerable energy allowances to the network operator.

SMALL CELL DEPLOYMENT IN CELLULAR NETWORKS

In this section, we shed light on typical small cell deployment models within cellular networks and discuss their implications on energy-related issues. Furthermore, the need for introducing SLEEP modes in small cells is highlighted for a heterogeneous network deployment. The next sections build on this motivation to describe specific SLEEP mode activation algorithms.

A small cell is a low-power low-cost radio BS whose primary design objective is to provide superior cellular coverage in residential, enterprise, or hot spot outdoor environments. Examples, in order of increasing cell size, include femtocells, picocells, and microcells. The terminology of femtocells, picocells, and microcells can be interchangeable; hence, it is important to focus only on the key commonalities of these smaller sized cells. In general, radio coverage of small cell BSs can range from tens of meters to a

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few hundred meters, and herein lies the first obvious energy saving from small cells. Due to shorter distances between the transmitter-receiver pair, the transmit power required to achieve the same quality of service (QoS) scales down significantly in the small cell scenario. This transmit power reduction bodes favorably for power requirements of related BS hardware components, and the overall BS power drawn from the socket recedes. One example of a typical small cell overlay network, where several small cell BSs provide coverage within a macrocell, is shown in Fig. 1.

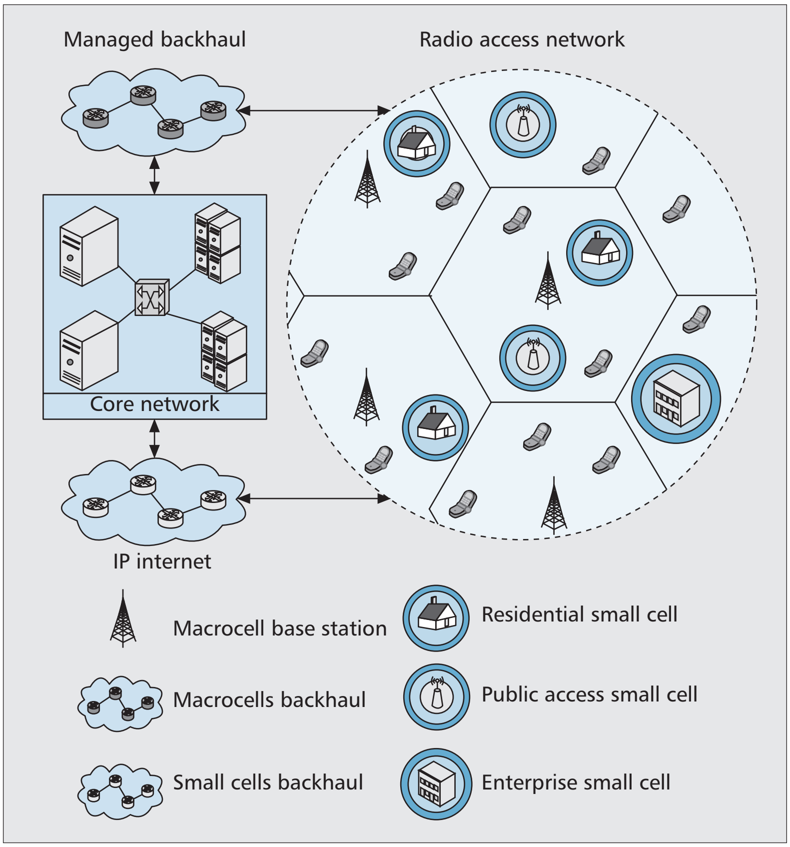

Figure 1. *Heterogeneous cellular network topology incorporating different forms of small cell deployments as an overlay on the macrocell network. Small cells may use secure tunnels back to the core network using existing broadband infrastructure.*

An important characteristic of small cell deployment is that it is considerably less planned as opposed to typical macrocellular deployments. For instance, in the case of residential femtocells, BSs are user-deployed and support plug-and-play deployment. Such a deployment strategy is enabled through the use of specialized self-x[1] algorithms, which run in small cell BSs and provide distributed control in a cellular network. Concurrently, the same distributed control can be used to invoke SLEEP mode procedures in small cells in a bid to reduce network energy consumption. We discuss these decentralized small cell controlled SLEEP procedures in more detail later.

There are two main operational modes for small cell BSs: *open access mode*, in which the BS allows access to all users of the operator's network; and *closed access mode*, which allows only registered users to access the small cell. The *hybrid access mode*, in which a limited amount of small cell resources are available to non-registered users, can also be available. The energy saving procedures employed in small cell BSs can vary significantly based on the access control mechanism. For instance, in the case of SLEEP mode schemes for closed mode small cells, the BS hardware might need to verify whether the subscriber requesting access to resources is registered or not, before switching itself ON. Other criteria, such as user location information, user classification, etc., are also integrated differently in algorithms based on the small cell mode of operation. These phenomena are described exhaustively later.

In order to provide a first order indication on the power consumption performance of small cell deployment, let us consider a Long Term Evolution (LTE) based cellular network in an urban area comprising of macrocells and picocells. The picocells are all user-deployed in respective households. The number of macrocell sites and picocells are denoted by η_{macro} and η_{pico}, respectively. It is assumed that a total of 40,000 mobile subscribers are present in the area with 10,000 users uniformly distributed outdoors and 30,000 users located indoors. The indoor user distribution is based on an average of 4 users per household, such that a maximum of 7,500 picocells can be deployed in all households. Each outdoor or indoor subscriber is assumed to have the same average traffic requirements of 0.5 Mb/s.

Each picocell draws P_{pico} = 12 W from the power socket [3], and can transmit up to 0.2 W and serve four simultaneous users. Each macrocell site consists of three sectors and consumes a total power of P_{macro} = 2.7 kW [2]. No dynamic power saving modes for macrocells are assumed; the power consumption remains fixed irrespective of the supported traffic. An average spectral efficiency of 1.7 b/s/Hz per macrocell sector is assumed [4], and by considering 20 MHz carrier bandwidth, 204 simultaneously active users can be supported per macrocell site, each requiring 0.5 Mb/s. The total energy consumption per annum (= 8760 h) of the network can be written as

$$E_{network} = (\eta_{macro} \cdot P_{macro} + \eta_{pico} \cdot P_{pico}) \cdot 8760, \quad \text{[Watt hours]} \tag{1}$$

under the assumption that core network components can be neglected for both macro- and picocells since their contribution to the total network energy consumption is very low. Based on the mixed voice and data traffic modeling in [3], each mobile subscriber is assumed to have a duty cycle of 17.15 percent. This means that, on average,

$$\left\lceil \frac{40{,}000 \times 0.1715}{204} \right\rceil = 34$$

macrocell sites are required to provision the modeled environment.

Using Eq. 1, Fig. 2 plots $E_{network}$ as a function of number of deployed picocells. As the percentage of users served by the picocells increases,

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[1] *Self-*x *refers to self-configuration, self-optimization, self-healing, and so on.*

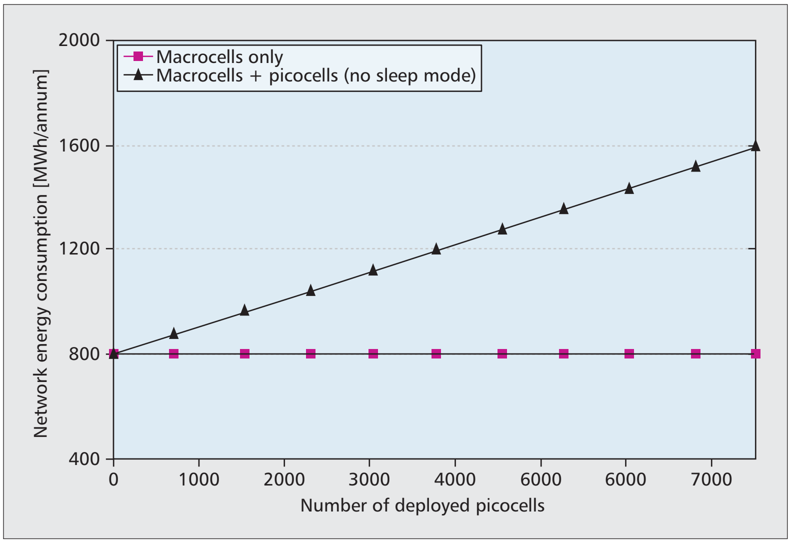

Figure 2. *Energy consumed by radio BSs per annum in dependency of the overlay picocell deployment. Each macrocell and picocell consume 2.7 kW and 12 W, respectively.*

the macrocell traffic load is correspondingly reduced. However, due to the inability to adapt its power consumption with traffic load, the energy consumption of the macrocell network remains constant throughout. The graph highlights that the network energy consumption increases linearly with the introduction of picocells due to more power-drawing sources in the network. As such, the network gets excessively overprovisioned (in terms of system capacity) as the deployment of picocells scales up, resulting in an increase in the probability of under-utilized BSs. This lays strong importance on devising SLEEP mode algorithms for radio BSs in a heterogeneous network setting. It will enable an ultra-efficient cellular network that has substantial user capacity in reserves, and can elegantly provision significant reductions in energy expenditure and consequently the energy operating expenditure (OPEX) of the network operator.

HARDWARE DESIGN FOR SMALL CELLS

A thorough understanding of the small cell hardware is required to design SLEEP mode algorithms that can utilize the switching off of various hardware components in low traffic conditions. Also, it is imperative to scrutinize the limitations of current hardware design in terms of its compatibility with SLEEP mode mechanisms. Keeping this view as the backdrop, this section elucidates the hardware model for small cell BSs.

Figure 3 illustrates a high-level schematic representation of a typical femtocell hardware design. It comprises a microprocessor that is responsible for implementing and managing the standardized radio protocol stack and the associated baseband processing, along with administering the backhaul connection to the core network. This capability is generally implemented as a multicore application-specific integrated circuit (ASIC), which has the added benefit of low power consumption. Apart from the on-chip memory, one or more random access memory components are connected to the microprocessor, which are required for various data handling functions and system bootup. The design also contains a field-programmable gate array (FPGA) and some other integrated circuitry to implement a host of features, such as data encryption, hardware authentication, and network time protocol (NTP). The radio component within the FPGA acts as an interface between the microprocessor and the radio frequency (RF) transceiver. Although not as cost effective, the existence of an FPGA in the hardware model can provide the much needed flexibility for integrating proprietary solutions in the small cell hardware. An active cooling component is not included in the hardware model because the current femtocell hardware is designed to be cooled by natural convection, and we assume that it will be the norm for most small cell hardware in the future. There are separate RF components for data transmission and reception, each consuming a certain amount of power. An RF power amplifier (PA) is present to pass a high-power signal to the transmitting antenna. Due to extremely important cost implications in small cell hardware design, a cost-efficient and robust PA with high linearity and gain is required. Typically, the power added efficiency (ratio of RF power gain to DC power IN) of such PAs can range from 5–40 percent, depending on the output RF power from the PA.

Table 1 shows the nominal power consumption profile of the small cell hardware components highlighted in Fig. 3. By assuming static power consumption across all traffic load, the hardware circuits consume a total of P_{ACT} = 10.2 W when fully active (RE state). With 85 percent power efficiency of the power supply, the power drawn from the power socket amounts to 12 W.

SLEEP MODE PROCEDURES FOR SMALL CELLS

The basic idea underpinning SLEEP mode activation in small cell BSs is the introduction of a low-power state in the hardware, referred to as the SLEEP state. We assume that the small cell resides in exactly one of the following states at any given time:

READY state (RE). In this state, all hardware components in the small cell BS are fully switched ON. The pilot channel RF transmissions are carried out to achieve a certain radio coverage area, and all allowed users in the coverage area are served by scheduling radio resources on data channels. All traffic is served under the constraints of the BS's maximum capacity.

SLEEP state (SL). In this state, some of the hardware components in the small cell BS are either completely switched off or operated in low-power modes. The BS is correspondingly said to reside in SLEEP mode. The exact components to be switched off are a function of the specific hardware architecture and the particular energy saving algorithm. This, in turn, has a

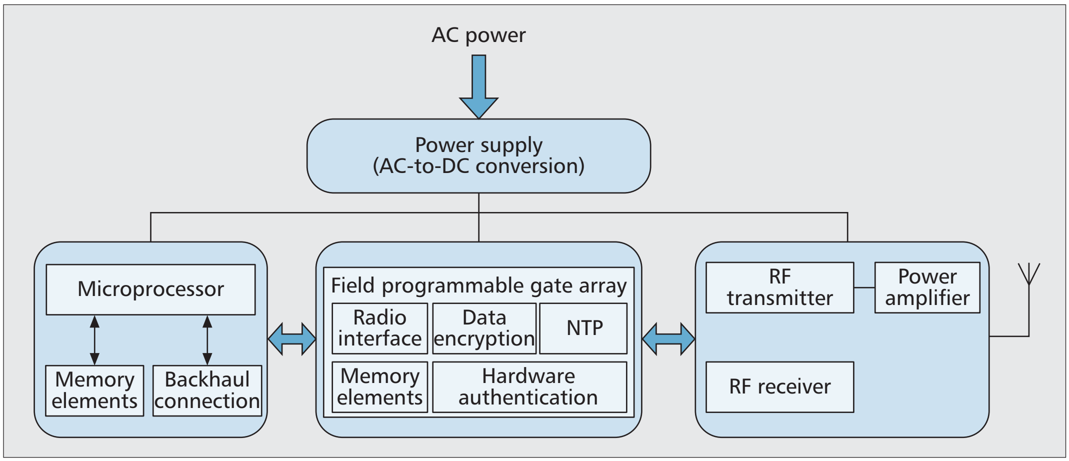

Figure 3. *Typical hardware model for a femtocell BS.*

By leveraging on the presence of sufficient underlay macrocell coverage, the small cell hardware can be augmented with a low-power sniffer capability that allows the detection of an active call from a UE to the underlay macrocell.

direct influence on the transition time between the SL and RE states.

In the following, we introduce three strategies to enable the transition of small cell BSs between the SL and RE states (i.e., SLEEP mode activation/deactivation). These mechanisms differ fundamentally in terms of the placement of SLEEP mode control in the network, which can be either at the small cell, in the core network, or driven by the user equipment (UE).

SMALL CELL CONTROLLED SLEEP MODE

By leveraging the presence of sufficient underlay macrocell coverage, the small cell hardware can be augmented with a low-power *sniffer* capability that allows the detection of an active call from a UE unit to the underlay macrocell. By doing so, the small cell can afford to disable its pilot transmissions and the associated radio processing (SL state) when no active calls are being made by the UE in its coverage area. When a UE unit located inside the sensing range of the small cell sniffer connects to the macrocell, the sniffer detects a rise in the received power on the uplink frequency band. This rise in the noise floor is easily detectable since the UE transmits at high power to the macrocell while being located very close to the small cell. If the received signal strength exceeds a predetermined threshold, the detected UE is deemed close enough to be potentially covered by the small cell. At this point, the small cell switches to the RE state and activates its processing and pilot signal transmission. The active UE in range of the small cell can then report the small cell pilot measurements to the macrocell. If the UE is allowed access to the small cell, the macrocell-to-small cell handover of UE will be initiated; otherwise, the small cell can revert to SLEEP mode. Upon the completion of the handover process, the small cell serves the UE until its connection is terminated, after which it can switch back to the SLEEP mode.

Note that this procedure requires macrocellular coverage since it relies on detecting transmissions from a UE unit to a macrocell. Therefore, the small cell needs to check whether sufficient macrocell coverage is available, which can be detected via measurements of the macrocell's pilot channels at the small cell and by UE measurement reports. In addition, the sniffer-based SLEEP mode requires one macrocell–small cell handover per connection; however, the benefits of reduced mobility events and associated signaling due to switched off pilot transmissions outweigh this [3].

Hardware component	Power consumption (W)
Microprocessor Associated memory Backhaul circuitry	1.7 0.5 0.5
FPGA Associated memory Other hardware functions	2.0 0.5 1.5
RF transmitter RF receiver RF power amplifier	1.0 0.5 2.0

Table 1. *Power consumption profile of femtocell hardware.*

In order to gauge the power savings based on the technique described above; the RF transmitter, PA and few non-essential hardware functions (approximately 1 W) can be switched off in idle conditions. This results in a total power saving of approximately 4 W. The existing RF receiver is employed for sniffer functionality that consumes 0.5 W. This means that the FPGA is kept ON to act as the interface between the sniffer and microprocessor, which maintains synchronization and backhaul connectivity with the core network. By looking up values from Table 1, a from-the-socket power saving of 4.7 W is achievable. This equates to a power saving upper bound of 39.2 percent with an always-on backhaul connection with the core network, such that the transition time from SL to RE states is on the order of milliseconds.

CORE NETWORK CONTROLLED SLEEP MODE

Different from the proposition above, this case does not require the low-power sniffer in the small cell to detect active UE. Alternatively, the transition of small cell from SL to RE state is controlled by the core network via the backhaul using a wake-up control message. The assumption of the underlay macrocell providing coverage to UE also applies in this case. Furthermore, the small cell BS can be configured to reside in the SL state by default and move to the RE state as explained next.

A connection between the macrocell and camped-on UE is set up after a paging message is transmitted to the UE in the downlink or an uplink connection request from the UE is made to the macrocell. After a successful connection setup, the appropriate core network element identifies the serving macrocell of the UE and verifies if there is any UE-associated small cell in the same macrocell region. For instance, this verification can be performed via the mobility management entity (MME) in LTE, a network element that keeps UE context information. The associated small cell BS to which the tagged UE is allowed to connect is then sent a wake-up message via backhaul to transition to the RE state and serve the UE. With respect to the small cell driven solution described before, the core network controlled solution has the following advantages:

- As opposed to the small cell driven solution, the core network controlled mechanism allows the distinction of registered and unregistered users. In the sniffer-based strategy, a small cell BS operating in the closed mode can unnecessarily switch itself on by detecting a noise rise from an unregistered user in its vicinity. The problem gets further aggravated if the BS is located in a busy area with lots of active users passing by.
- The core network driven approach allows the possibility to take a centralized decision, based not only on a particular UE but also taking into account the macrocell traffic load, user's subscription and traffic behavior, type of service requested, and so on.
- The core network driven approach allows the exploitation of UE location estimation (or positioning) in order to further improve the decision efficacy. For example, the UE can pass its location information to the core network, in both the idle and connected modes, such that the network can make a more informed decision on activating/deactivating nearby small cells. The UE could be configured to either update its location periodically, only when it changes, or at the time of connection establishment.

It is important to emphasize that although the core network driven method provides better activation control, it incurs control signaling over the backhaul to wake up small cells. As an example, a single wake-up control packet could be used to trigger the activation/deactivation of a small cell BS.

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By referring to the hardware abstraction in Fig 3, the core network driven procedure provides a couple of choices in terms of switching off specific hardware components. One option is based on implementing the backhaul data processing in the microprocessor, which would switch off all hardware parts except for the backhaul circuitry (e.g., Ethernet switch) and microprocessor. This results in power consumption of approximately 3 W in SLEEP mode — a saving of 75 percent. The other preference could be based on implementing the wake-up control in the backhaul switch itself, thus allowing for the microprocessor to be switched off also. This can further reduce the SLEEP mode power consumption to approximately 1 W — a saving of 92 percent. We note that, if architecturally possible, the microprocessor can also run in low-power mode in both cases due to reduced processing load.

UE CONTROLLED SLEEP MODE

A third approach is to place the SLEEP mode control at the UE side, which can broadcast wake-up signals in order to wake up small cell BSs within its range. The small cell, when in SL state, retains the capability to receive wake-up signal transmissions from the UE, and any time such signals are received, it transitions to RE state. This solution can principally be used when the UE is in idle mode, whereas the small cell driven and core network controlled solutions require the UE to establish a connection with the network. The UE broadcast can also contain identification information such that the closed mode small cell wakes up only to registered UE.

This solution can be implemented in various ways. The UE can broadcast periodic wake-up signals continuously so that any small cells in SL state will transition to RE state when the UE approaches it. This means that coverage provided by small cells "follows" a UE unit as it moves around and ensures that UE units are given small cell coverage whenever possible. On a negative note, this implementation decreases the amount of energy savings as the small cells would spend more time in RE state actively listening for UE wake-up signals. As a direct consequence, UE battery consumption increases due to periodic broadcasts.

An alternative implementation strategy is for the UE to broadcast wake-up signals when required on demand, such as in the absence of sufficient macrocell coverage or for higher data rate requirements. In such a situation, the UE can transmit broadcasts to attempt to wake up any small cells within range. The UE can also perform these broadcasts prior to establishing a connection with the network. This enables the UE to wake up any small cells first and then connect directly through a small cell. The on-demand approach can result in better energy savings since the small cell can be in SL state more often, and is only transitioned to the RE state when required.

The UE controlled solution has the following advantages over the small cell driven and core network controlled solutions:

- The UE controlled approach does not rely on the need for underlay macrocell coverage to switch ON/OFF small cells. This is particularly important as many small cells could be deployed as a means of solving macrocell coverage black spots. Both small cell and core network controlled solutions require sufficient macrocell coverage for the UE in order to enable SLEEP mode activation/deactivation.

- The amount of core network related signaling is reduced. Whenever the UE makes a call, it does not have to initiate a connection with the macrocell underlay and then get handed over to the small cell after it transitions from SL to RE state. Based on the UE driven approaches described above, the small cell would already be in the RE state at the time of connection establishment allowing the UE to initiate connection directly with it.
- The approach allows the implementation of a "coverage follows UE" principle without acquiring specific UE positioning and hence saving on the transmission of such information.

In order to provide fast switching time between SL and RE states in the UE controlled method, the RF transmitter, PA, and certain miscellaneous components can be switched off in SL state to obtain a from-the-socket power saving of 4.7 W, akin to the small cell driven method. This would enable instantaneous BS switch-on upon receiving the UE broadcast.

Requisites for Sleep Mode Activation in Small Cells

Flexible Hardware Design

An obvious drive to reduce the small cell power consumption is to design and produce hardware components that inherently consume less power. However, substantial energy savings can be achieved by modulating the hardware energy consumption over the traffic load. In other words, the power drawn by the individual hardware parts should scale with traffic demands, and these should also support ultra-low-power modes in zero load or idle conditions. For instance, the microprocessor can vary its clock speed depending on the number of UE units served such that the processing power consumption follows user traffic.

Moving on from individual hardware components, the overall hardware design needs to be SLEEP mode aware and sketched with energy constraints in mind. One shortcoming of the hardware design described in Fig. 3 is the dependence of different hardware components on each other, which prevents the individual switching off of elements in SLEEP mode. For instance, FPGA acts as a communication interface between the RF transceiver and the microprocessor and cannot be switched off independently. A modular hardware design approach, which provides the flexibility of handling components individually, can offer a significant improvement over the current model.

Macrocell Network Adaptation

The utilization of macrocells can be reduced due to offloading of user traffic to small cells. Small cells are ideal for providing localized high data rate services, while macrocells are better suited for providing coverage over a wide area. Therefore, the joint use of small cell overlays in hotspots to provide additional capacity, with an underlay macrocell for wide area coverage is an efficient way of deploying cellular networks in scenarios where demand for capacity is non-uniformly distributed. However, the rewards from such a conjoint arrangement are fully reaped only if the underlay macrocell network is designed to work in tandem with the small cell deployment. In the following, various techniques that can be used on the underlay macrocell to maximize the energy efficiency of cellular networks are discussed.

Consider the scenario where a macrocellular network has been carefully planned, deployed, and provisioned to provide the required coverage and capacity to the existing users. With the introduction of small cell overlays, the macrocell network becomes over-provisioned due to the offload of traffic by means of small cells. One strategy for the network operator is to keep the existing macrocell BSs as they are, and delay any modifications or capacity upgrades until natural growth in user demand catches up with the spare capacity. This approach does not offer the most efficient energy savings since it may take a long time for growth in user demand to increase sufficiently. Alternatively, the network operator can re-optimize the existing macrocell network in response to small cell deployment, such as decommissioning sites that are no longer needed. Performing this optimization can be costly and disruptive in the short-term but will make the overall network more energy-efficient and reduce network OPEX over the long term.

An interesting scenario is when the small cells are user-deployed, such as residential or enterprise femtocells, where they can be deployed or removed from the network without warning. This highly dynamic and unpredictable nature of small cell deployment makes frequent manual re-optimization of the macrocell network impractical. It is therefore desirable for the macrocell BS to dynamically scale back its power consumption according to the supported traffic load. This could be achieved by using various approaches, such as dynamically switching off carriers and traffic modules according to load conditions, and using multistage power amplifiers [5] that allow the transmit powers to be adjusted more efficiently. Self-organizing algorithms also allow a BS to reconfigure and compensate when neighboring BSs switch off. By implementing these steps in the macrocell BS, the heterogeneous network is able to fully capitalize on its energy reduction potential.

This highly dynamic and unpredictable nature of small cell deployment makes frequent manual re-optimization of the macrocell network impractical. It is therefore desirable for the macrocell BS to dynamically scale back its power consumption according to the supported traffic load.

Results

In this section, we reuse the heterogeneous network model delineated earlier and illustrate potential energy savings from SLEEP modes in small cells. In order to calculate the average network energy consumption with SLEEP mode enabled picocells using Eq. 1, the average power consumption from picocell BSs $\overline{P_{pico}}$ is calculated as

$$\overline{P_{pico}} = \overline{\eta_{pico,RE}} \cdot P_{pico,RE} + \overline{\eta_{pico,SL}} \cdot P_{pico,SL} \quad (2)$$

where $\overline{\eta_{pico,RE}}$ and $\overline{\eta_{pico,SL}}$ represent the average number of picocells in RE state and SL state, respectively, and $P_{pico,RE}$ and $P_{pico,SL}$ denote the picocell power consumption in RE and SL states,

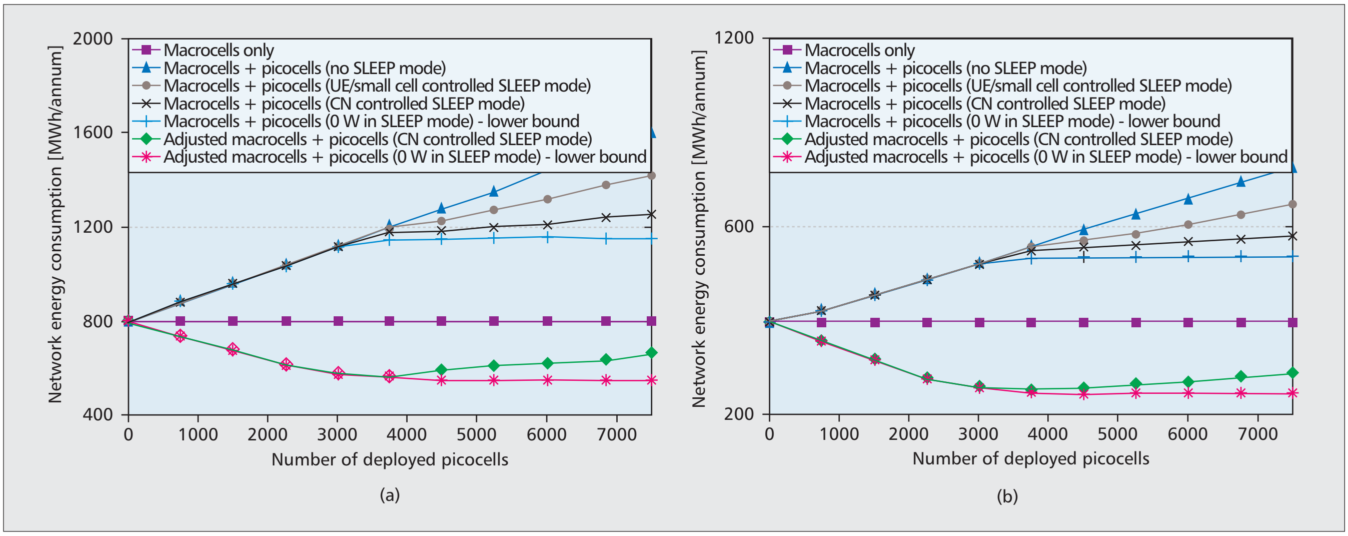

Figure 4. *Energy consumed by radio BSs per annum in dependency of SLEEP mode enabled picocell deployment. Each macrocell and picocell consume (a) 2.7 kW and 12 W, and (b) 1.317 kW and 5 W, respectively.*

respectively. To calculate $\overline{\eta_{pico,RE}}$ and $\overline{\eta_{pico,SL}}$, we first compute the average number of active indoor users using the duty cycle of 17.15 percent [3] (i.e., 30,000 × 0.1715 = 5145). This means that to serve these indoor users, a maximum of 5145 active picocells are required if indoor users distribution is such that each picocell serves one user. Similarly, a minimum of $\lceil 5145/4 \rceil = 1287$ active picocells are required, if each picocell can serve 4 indoor users. This results in a mean of $\overline{\eta_{pico,RE}} = 3216$ active picocells. For example, if a total of 5000 picocells are deployed, an average of 3216 picocells will be active at any given time and $\overline{\eta_{pico,SL}} = 5000 - 3216 = 1784$ picocells will reside in the SL state.

Figure 4 is an extension of Fig. 2 that now shows the average network energy consumption [MWh/annum] in dependency of the proposed SLEEP mode algorithms. Figure 4a is plotted with the same power consumption values as in Fig. 2, that is, $P_{macro} = 2.7$ kW, $P_{pico,RE} = 12$ W, and $P_{pico,SL}$ equals 7.3 W and 3 W for UE/small cell driven[2] and core network controlled methods, respectively. Figure 4b focuses on a more energy-efficient hardware design of future cellular BSs, whereby a remote radio head (RRH) configuration is considered for macrocell BSs resulting in $P_{macro} = 1.317$ kW [6], $P_{pico,RE}$ is assumed to be 5 W [7], and $P_{pico,SL}$ is set as 3.04 W and 1.25 W for UE/small cell driven and core network controlled methods,[3] respectively.

Figure 4 illustrates that by virtue of switching off more components in the SL state, the core network controlled solution is shown to provide higher energy savings than the small cell and UE driven methods. By examining Fig. 4a and the case where a picocell is present in each household and all indoor traffic is supported by picocells, UE/small cell driven and core network controlled approaches provide savings of 11.1 percent and 21.2 percent, respectively, with respect to the absence of SLEEP modes in picocells. Furthermore; to asses the maximum achievable gains, the lower bound on the network energy consumption with SLEEP mode and fixed macrocell power is also plotted. The bound is based on the assumption of 0 W power consumption in SLEEP mode.

Figure 4 also provides an indication on the network energy consumption with adjusted macrocell configuration. With the offloading of traffic, the macrocell network is assumed to be reprovisioned and the required number of macrocell sites η_{macro} and corresponding total power consumption are recalculated. As a result, the energy reduction gains are much higher since a lower number of macrocell BSs are required. For instance, in Fig. 4b at 7500 picocells, core network controlled SLEEP mode consumes approximately 60 percent less energy than no SLEEP modes. Moreover, the lower bound with adjusted macrocell network highlights the energy saving potential of a heterogeneous deployment where both macrocells and small cells can adapt dynamically as per their traffic requirements. The plots show that due to offloading of traffic to small cells and consequent dynamic switch-offs of macrocells, the overall power consumption of the radio access network is lower than the case of no small cells in the network, coupled with substantial capacity incentives that come inherently with small cell deployment. We note that the plots in Fig. 4 follow a linear profile due to the conservative assumption of uniform traffic offloading. In practice, user traffic distribution is non-uniformly distributed, which means that some macrocell sites are more loaded than others. In such a case, a small proportion of small cells can offload large amounts of macrocell traffic leading to more beneficial non-linear energy gains.

CONCLUDING REMARKS

We introduced a class of energy-efficient SLEEP mode algorithms for small cell base stations. The proposed algorithms allow the hardware components in the BS to be astutely switched off in idle conditions, such that the energy consumption is modulated over the variations in traffic load. Three different strategies for algorithm control have been discussed, relying on small cell driven,

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[2] *As discussed earlier,* $P_{pico,SL}$ *is the same for both UE driven and small cell controlled approaches.*

[3] *These values are calculated to maintain the same power reduction factor as in Fig. 4a.*

core network driven, and user equipment (UE) driven approaches. The importance of macrocell adjustments with small cell deployments has also been discussed. Based on a mix of voice and data traffic model, the algorithms have been shown to offer approximately 10–60 percent energy savings in the network compared to no SLEEP modes in small cells. The power consumption model adopted in the article focuses on the network's radio access part and does not include the power consumption of UE. With small cell deployment, the transmitter-receiver distances are greatly reduced, resulting in reduced transmission power and hence extended battery life for UEs. Future studies will take into account these UE aspects, backhaul energy consumption, and non-uniform traffic distribution. Also, the implementation and testing of SLEEP mode techniques in real-life testbeds is vital for their future integration in cellular networks.

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BIOGRAPHIES

IMRAN ASHRAF (imran.ashraf@alcatel-lucent.com) received a B.Sc. degree in electrical engineering (major in telecommunications) from the University of Engineering & Technology (U.E.T), Lahore, Pakistan, in 2002. He obtained his M.Sc. in mobile and personal communications in 2003, and a Ph.D. in telecommunications in 2007, both from King's College, University of London. From 2003 to 2005 he worked for the Core 3 research program of the Mobile Virtual Centre of Excellence (M-VCE), United Kingdom. From 2006 to 2007 he was a research associate at the Centre for Telecommunications Research, King's College London, where he contributed to EU-funded research projects on wireless sensor networks. He joined Bell Laboratories, Alcatel-Lucent, United Kingdom as a member of technical staff in 2007. His research interests include protocol design and performance analysis of wireless ad hoc and sensor networks, cross-layer issues, efficient scheduling algorithms, and self-organizing behavior in cellular radio networks.

FEDERICO BOCCARDI received a Laurea degree in telecommunication engineering from the University of Padova, Italy, in 2002 and a Ph.D. in electronic and telecommunication engineering from the same university in 2007. From October 2004 to April 2005 he was a visiting student at Eurecom, Sophia Antipolis, France. From November 2005 to May 2006 he was a visiting student at Bell Labs, Holmdel, New Jersey. Since December 2006 he has been with Bell Labs, Alcatel-Lucent as a member of technical staff. His research interests include signal processing for wireless communications and PHY/MAC layer system design. Since 2009 he has been participating in the standardization activity for LTE-advanced.

LESTER T. W. HO is a Distinguished Member of Technical Staff in the Autonomous Networks and Systems Research Department at Bell Labs in Swindon, United Kingdom. He studied at Queen Mary and Westfield College, University of London, where he received a B.Eng. in electronic engineering and a Ph.D. on the topic of self-organizing behavior in wireless networks. At Bell Labs, he has been working on autoconfiguration and dynamic optimization of wireless networks, protocols and algorithms for flat cellular network architectures, dynamic spectrum allocation, and techno-economic modeling of future wireless business models. His current research interests include small cell network deployments, evolutionary algorithms and machine learning applied to autonomous networks, and improving the energy efficiency of networks.

Future studies will take into account these UE aspects, backhaul energy consumption, and non-uniform traffic distribution. Also, the implementation and testing of SLEEP mode techniques in real-life testbeds is vital for their future integration in cellular networks.