Towards Green Wireless Access Networks (Invited Paper)

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***Abstract*—As wireless communications experience exponential growth, energy consumption has became a crucial problem in the wireless industry. Energy efficiency of wireless systems has to be significantly improved in order to guarantee the sustainable growth of the wireless industry. Plenty of efforts have been carried on to achieve so called green wireless world. In this paper, focusing on energy saving in wireless access networks, we provide an overview on energy saving studies currently conducted in 3GPP LTE standard body. The aim of the paper is to gain a better understanding on energy consumption problems in wireless access networks and identify key research problems in this field. Currently most of research focus on base station energy saving with efforts to reduce energy consumed by power amplifiers. Less attention are spent on the network level. We believe a holistic network level solution based on novel architecture and methods, such as relay, user cooperation, as well as cognitive approaches, will be prosing enablers towards green wireless access networks.**

I. Introduction

The rapid growth of wireless communications raises a critical energy consumption problem. On the one hand, the number of mobile devices increase in an extremely fast pace. Anticipated by Garnter, by 2013 browser-equipped phones will exceed 1.82 billion units and the mobile phone will surpass PC as the most common web access device worldwide [1]. The direct impact is that much more energy will be consumed by newly deployed wireless infrastructure. On the other hand, data-intensive services, like multimedia and data services, begin dominating mobile devices. High data rate required by those services comes with the cost of high energy consumption. The data volume through networks is expected to increase approximately by a factor of ten every five years, which associates with 16% to 20% increasing of energy consumption [2]. Applying this rate to mobile communications, which contribute to 15% to 20% of the entire Information and Communications Technologies (ICT) energy footprint [2], the wireless industry faces a sustainable development problem on energy consumption. It is important to develop energy efficient wireless technologies to meet this challenge and enable green wireless communications.

According to design purposes and use scenarios, wireless networks have many kinds. The difference on architecture affects energy distribution in the network, and in turn corresponding energy efficient solutions. We focus on wireless access networks in this paper for several reasons. Firstly, wireless access networks are most widely deployed wireless networks in the world. Energy efficient solutions designed for wireless access networks will significantly contribute to energy saving in the ICT sector. Roughly speaking, any point to multiple point wireless system with a base station (BS) or an access point (AP) connected to the core network or Internet belongs to the broad definition of wireless access network. We use the term network and system exchangeably in this paper, as a wireless access network normally refers to a wireless access system. In our definition, wireless access networks span from wireless wide area networks (WWAN), wireless local area networks (WLAN), to wireless personal area networks (WPAN). The system of interest in this paper is WWAN. More specifically, we focus on the solutions for 3GPP Long Term Evolution (LTE) systems. Secondly, there is urgent demand for energy efficient solutions from users to support better mobility experience. Thirdly, as seen from standards, currently standards of wireless access networks are designed for best performance. Only recently energy efficiency of wireless access networks has been receiving increasing attention. Much space remains to achieve a better balance between performance and energy saving.

From a broad sense energy consumed by a system consists of two parts: embodied energy to manufacture and deploy the system, and operating energy to run the system. Embodied energy is not directly related to communication itself. Keeping in mind that embodied energy is an important factor to be considered in design of a new generation wireless system, we focus in this paper only on operating energy, as our main concern is to overview energy efficient solutions for existing systems.

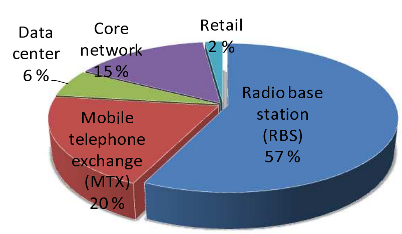

Fig. 1. Energy consumption composition in Vodafone. Source: Vodafone.

As shown in Fig. 1, statistics indicate that the BS is the main source of energy consumption in a mobile operator. Energy efficient solutions for wireless access networks are mainly focus on BSs. Among all components in a BS, power amplifiers (PA) consume most of energy. Most of energy is lost in the conversion process of a power amplifier. Other energy can be saved are energy lost in cabling and alternating current/direct current (AC/DC) converting, and energy used to drive cooling fans. As shown in [3], for a Global System for Mobile Communications (GSM) BS, to provide 120W of efficient output to antennas, the BS needs to be powered at 3802W. The overall efficiency is only 3.1%. Various solutions are proposed to increase energy efficiency of the BS from different aspects: increasing PA efficiency, using non-active cooling techniques, using masthead PA to reduce feeder loss, using energy efficient backhaul solutions, applying energy efficient deployment strategies, and improving protocols for energy efficiency.

This paper reviews soft methods to improve energy efficiency of wireless access networks, with a focus on BS solutions in LTE systems. In LTE the BS is called eNobeB, however we use the term BS through the paper. Moreover by BS we mean a radio BS (RBS). Soft methods refer to solutions based on changes in protocols, architecture, and deployment strategies. Soft methods provide flexible and cost efficient solutions with minimum impact on hardware. They are derived from the fact that currently energy consumed by a BS does not scale with its traffic load. By adapting the configuration of a BS with the traffic load, significant energy saving can be achieved.

The paper is organized as following. In the next section, we provide a power consumption model of a GSM system and highlight the power consumption of main components in the system. We use this model to identify energy consumption problem in similar systems. In Section III, the overview on energy saving efforts in LTE standardization is summarized. The advantages and disadvantages of the proposed solutions are analyzed. A simple performance comparison is provided to show efficiency of those solutions under a daily traffic pattern. Since the study in Section III are mainly focused on the BS side, in Section IV, new methods at the network and system level are introduced. We believe those new methods are promising to push energy efficiency of wireless systems to a new level. To enable green wireless access systems, key research problems are also summarized in Section IV. The conclusion is drawn in Section V.

II. Energy consumption model of BS

This section describes an energy consumption model for wireless access network. The aim is to understand how energy is consumed in a RBS of a wireless access network. Since BSs consume most of energy in a wireless access network, identifying energy consumption problems in a BS provides clues for better energy saving solutions for the whole system.

We provide a generic model for BS and analyze power consumption of a GSM BS. The reason for using reference data from a GSM system is that we can easily get those data from the public source. A Wideband Code Division Multiple Access (WCDMA) or LTE BS is expected to have similar order of power consumption as a GSM BS, although there is a trend that new generation of BS consumes less power.

The energy consumption reference model is defined in [4]. We only use the outdoor reference model here as the main difference between outdoor and indoor model is the climate control. As shown in Fig. 2, the reference model of a BS is composed by a BS equipment and support system infrastructure. A BS equipment is a network component which serves one or more cells and interface the mobile station through air interface and a wireless network infrastructure. Transceivers and associated power amplifiers are included in a BS equipment. The support system of a BS includes power supply, climate control for temperature control, transmission module connected to core network, and battery backup. The power loss of the battery backup is not taken into account in this model.

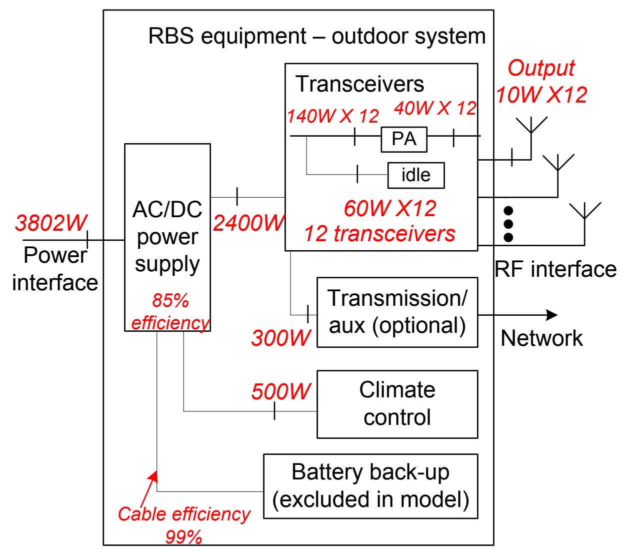

Fig. 2. Energy consumption reference model for BS. (Note: Values in italic are power consumption figures in GSM system.)

As seen from Fig. 2, for a GSM system with 12 transceivers, the feeding power from the AC power supply is 3802W. For each transceiver, the input power is 200W, among which 60W is consumed at idle time and 140W is used for transmission. The output power after a power amplifier is 40W, and the final power sent over air is only 10W. We can easily get in this case the PAs consumes 70% of the whole power, PA efficiency is 28%, and overall efficiency of the BS is only 3.1%. For a 3G BS, PA efficiency can be 45% and overall efficiency of a 3G BS is less than 12%. PA efficiency is still the main problem for overall energy efficiency.

It is clear that the PA is the main concern in energy efficient solutions for the BS. Physical constraints puts a significant limit on PA efficiency. PA efficiency of 60% is now the target by advanced power amplifier techniques. In addition to continuously improve PA efficiency, the alternative way is to switch off the PA when there is no traffic to transmit. Many energy saving proposals for the BS fall into this category. We will describe them in the next section.

III. BS ENERGY SAVING METHODS

This section summarizes LTE energy saving studies performed in the 3GPP standardization body. We assume readers have basic knowledge on the LTE standard. The reasons that only introduce solutions for the LTE system are following: for 2G and 3G systems, their standards are mature and therefore only limited space is allowed for energy saving due to the backward compatibility problem; LTE along with Worldwide Interoperability for Microwave Access (WiMAX) will be the mainstream of wireless access systems worldwide in a near future; ongoing energy saving studies for LTE are very active in the 3GPP standard body; LTE provides significant inputs for the future global mobile standard as known as the International Mobile Telecommunications (IMT)-Advanced system. According to the similarity between LTE and WiMAX, the solutions introduced for LTE may provide a good reference for WiMAX systems.

The philosophy behind all proposed methods is the same: making the energy consumption in the BS scale with the traffic load. Most methods introduced here target reducing PA operating time. Other solutions are possible, for instance, reducing the operating bandwidth so as to reduce the transmission power, or using the combination of different cell sizes to enable better energy consumption in a covered area. We divide those solutions into time, frequency and spatial domain and introduce them individually. Performance of different solutions is compared based on a realistic traffic pattern during a day. Note that hybrid approaches combined solutions from three domains are possible. The study in [5] showed the hybrid approach provided best energy saving performance.

We should emphasize that from the standard viewpoint those solutions can be divided into two categories: implementation based or standard impacted. The implementation based solutions require no changes in the standard and therefore are easily to be integrated in products. For standard impacted solutions, it is possible that they will never be included in the standards.

A. Time domain approaches

The common idea of time domain solutions is to shut down PAs whenever there is no traffic in the downlink. The energy saving is measured by the time fraction where PAs are off during a time period, normally measured by a frame. Before describing those solutions, it is worth briefly introducing the frame structure of LTE. In LTE, the channel is structured by contiguous time frames. Each frame consists of 10 subframes with a fixed length of 1 ms. Each subframe in turn has two equal sized time slots. According to the configuration, each time slot accommodates a number of Orthogonal Frequency Division Multiplexing (OFDM) symbols. Normally that number is 7. The structure of a downlink subframe is illustrated in Fig. 3, which includes symbols for control signals and data traffic. Among a variety of control signals, reference signals (RS) are regularly transmitted in each subframe, used to obtain downlink channel state information (CSI). If there is no or less downlink traffic, the frequency to transmit RSs can be reduced. So does the PA on time. This is the base for those time domain energy saving solutions.

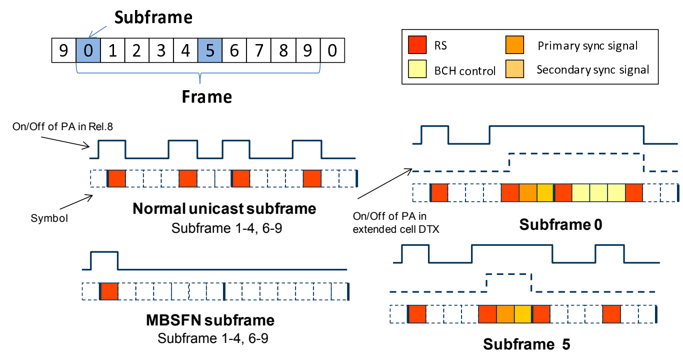

Fig. 3. Reduce control overhead in frame for energy saving in LTE.

There are three ways to shut down PAs for energy saving. The most straightforward approach is to turn off PAs for signal-free downlink data symbols. This is an implementation-based approach with no change to the standard. The downside is that the number of RSs remains the same. A simple calculation from the Fig. 3 shows that 47% of time in a frame PAs are in the operating mode [6]. The second approach, as shown in Fig. 3, uses Multicast broadcast single frequency network (MBSFN) structure to reduce RSs. MBSFN is proposed to deliver services such as Mobile TV using the LTE infrastructure. In a MBSFN frame, 6 subframes out of 10 only need to transmit 1 RS, while in the normal case it is 4 RSs. The PA on time is therefore reduced to 28% [6]. The feature of MBSFN has been included in LTE Release-8, therefore having no backward compatibility problem.

The most interesting solution is extended cell Discontinuous Transmission (DTX) approach [7]. This approach further reduces RSs as compared to the MBSFN approach. As shown in Fig. 3, if there is no downlink traffic, in the extended cell DTX mode there is no need to have any transmission in 8 subframes. The PA on time is further reduced to 7.1%. The extended cell DTX approach has some limitations. Firstly, it does not provide backward compatibility. Secondly, it only works when there is no downlink traffic. This traffic condition is very rare during a day. Thirdly, the reduction of RSs has impact on the performance of user equipments (UE). In LTE, some control procedures are performed with the assistance of RSs. Without enough RSs, UE may experience unpredictable problems in synchronizing with the BS or decoding control signals, therefore having negative impact on services. Moreover, Reducing RSs may prevent a UE from entering into the terminal DTX mode and then reduce the battery life. The debate to introduce extended cell DTX approach in the standard is still ongoing.

B. Frequency domain approaches

Two energy saving approaches are normally used in the frequency domain. The bandwidth reduction approach adapts the bandwidth with the traffic load. Less bandwidth is used when the downlink traffic load is low. As shown in Fig. 4, to maintain the same Power Spectral Density (PSD), smaller bandwidth requires less output power. The advantage of this approach is that it is suitable for low traffic load. However, this approach does not shut down the PA. As an operating PA consumes much more than an inactive PA, the energy saving from this approach may be marginal. Moreover, a PA normally operates at an optimized point with a given output power range. Reducing the output power will degrade the PA efficiency and in turn the gain for energy saving.

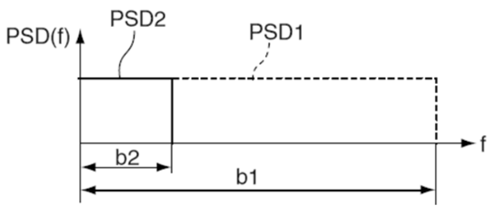

Fig. 4. Bandwidth change with same power spectral density.

Carrier aggregation is the second approach used for frequency domain energy saving. It assumes carriers are aggregated to groups and served by an individual PA. The idea is to shut down the associated PA when the corresponding aggregated carriers are not scheduled for traffic. This approach relies on the implementation of PAs in the BS. It is only applicable to BS which has aggregated carries and has separate PA attached to each carrier.

In general, frequency domain solutions have less impact to UE. However, due to the constraints mentioned above, the efficiency of frequency domain solutions is limited.

C. Spatial domain approaches

Reducing antenna number is the most common used energy saving approach in the spatial domain. It is illustrated in Fig. 5. In this case, if the branches of antenna are reduced from 4 to 1, energy consumption of transceivers is reduce to 1/4, as PAs associated with those branches can be shut down. Antenna number reduction approach can be used in the low traffic condition. The reduction of antenna branches decreases the total output power and makes cell size being shrunk. Additional mechanism is needed to maintain the strength of control signals at the cell edge. The bandwidth reduction approach can be applied here as less bandwidth requires less power. The antenna number reduction approach may lead to service degradation or interruption as the antenna reconfiguration causes delay. It is suggested to use this approach for semi-static load.

The cell switch-off approach [8] is a system level approach which works in an area covered by multiple cells. The system level approach means there is no need to modify the low layer components in the BS. When the traffic load in a given area is low, some cells can be shut down and the served UEs are handed over to remaining working cells. Those inactive cells can be turned on again during the busy time. There are two ways to switch on/off cells. One is the signaling directly between BSs. The other is the dedicated control from the

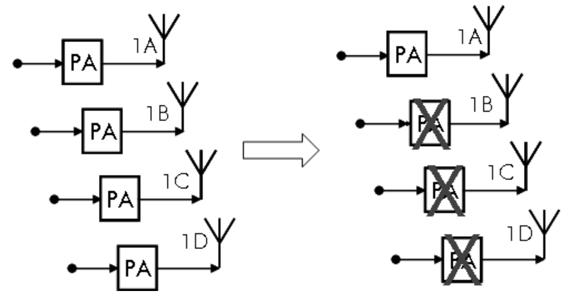

Fig. 5. Reduce antenna number for energy saving.

Operations, Administration, and Maintenance (OAM) layer of the system.

A special case of the cell switch-off approach is called the hierarchical cell structure (HCS) approach [9], in which always-on macrocells are deployed for basic coverage and small cells are used for capacity boost. Cells for capacity boost only operate when the traffic load is high in macrocells.

While the cell switch-off approach tries to make a good balance between performance and energy saving, it has limitations. Firstly, frequently switching on/off cells affects services in UEs. Its usage should be limited to a semi-static manner. Secondly, switching off cells may reduce the battery life of served UEs as they have to connect other cells far away. Thirdly, if switching off a cell creates uncovered area, remaining active neighboring cells need to increase their power to cover this area. This may make the energy saving gain become marginal.

D. Performance comparison

We use the result from [5] to show the actual performance of different energy saving approaches under a realistic daily traffic pattern. The daily traffic pattern is shown in Fig. 6, which includes 7 hours of low load time and 2 hours of idle time. It should be noted that different traffic patterns lead to different performance results.

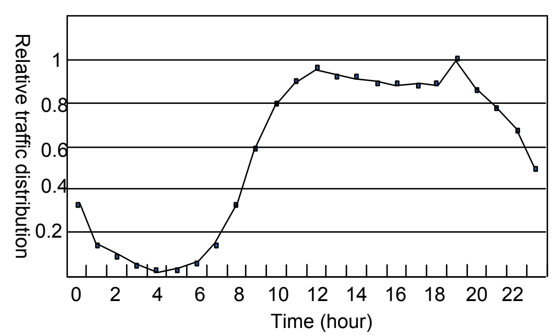

Fig. 6. Daily downlink traffic load pattern.

Fig. 7 shows the relative energy saving performance of different approaches as compared to the full load case. The energy saving approaches for no load scenarios, which are extended cell DTX and MBSFN for no load, achieve energy saving less than 8%. This is because the idle time only occupies a very small fraction of time during a day. The energy saving approaches working for low load scenarios provide better energy saving performance than those only working in no load scenarios. Among three low load approaches, MBSFN for low load provides highest performance. The bandwidth reduction approach outperforms the antenna number reduction approach. The best energy saving gain is achieved by a hybrid approach, which reconfigures the bandwidth, antenna numbers and carriers according to the traffic load in a semi-static way. More than 50% of energy saving is achieved in this approach.

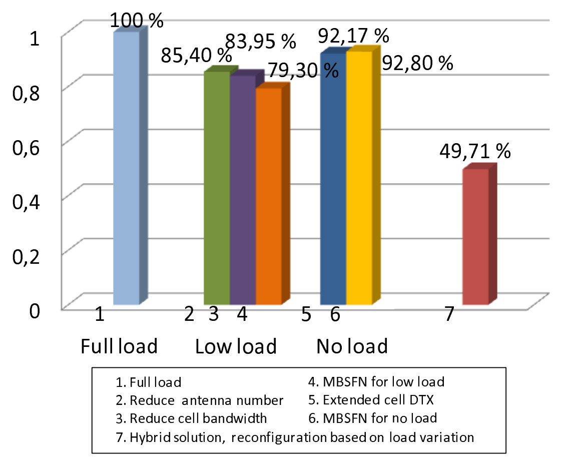

Fig. 7. Relative power consumption of energy saving solutions.

IV. Research directions

The previous section describes energy saving techniques used to improve BS efficiency. They are mainly applied in a single system. As stated in [2], to fundamentally improve energy efficiency of wireless systems, a holistical view is required. Fundamental research problems remain in this area.

The first step to solve those problems is to develop a clear understanding on energy consumption in current wireless networks in a wide range of scenarios. Most likely any energy saving solution comes with certain cost. The energy saving achieved in some components of a network may cause additional energy consumption in other components. Solutions need to be carefully evaluated from a holistic view, with all impacts taken into account.

Another challenge is to derive energy efficient metrics accurately and efficiently quantifying energy consumption. Those metrics are the key to evaluate energy saving solutions. The basic form of energy efficiency metrics is Bit/Joule or Joule/Bit. It is not always easy to get that figure when the measurement is not possible. Other metrics, for instance, km2/W or subscribers/W for cellular system [4], can be used. Note that measuring those metrics may cost additional energy.

One of the key research problems in energy saving is to make energy consumption scale with the traffic load, and further with services. It is a goal that can only be achieved using a holistic solution across all layers of protocol stack and heterogenous networks. Novel architecture and methods are demanded, most likely cross the boundary of currently isolated systems.

Relay in wireless access networks is a promising architecture to achieve energy saving. The energy saving in relay comes from the path loss saving. Studies showed the path loss reduction ranges from 21 dB for a cellular multi-hop system to 3-7 dB for a two-hop system [3]. It is worth studying relay strategies for energy saving in addition to throughput improvement.

Relay can be infrastructure based relay or mobile relay. In mobile relay a mobile device can temporally act as a relay node. This can be extended to a broadly defined relay scenario where a set of mobile devices setup a cooperative group sharing resource that benefits each other. We call it user cooperation, in which mobile devices equipped with both cellular and short range air interfaces provision services not only from cellular links, but also through cooperation from short range links. Initial study showed the potential of this new architecture to achieve energy saving from video services [10].

The most promising way to improve energy efficiency of wireless systems may lie in cognitive approaches, in which learning is used for better adaption [11]. Cognitive approaches can be used at the spectrum level for spectrum coexistence and interference management. It is specially important for dynamic spectrum access (DSA) scenario. Moreover, beamforming through Multi-Input Multi-Output (MIMO) antennas, powered by cognitive techniques, has great potential to isolate interference. Interference mitigation directly results in energy saving. Cognitive approaches can also be applied at the network layer to integrate heterogenous networks and let energy efficiency become one of primary optimization concerns to provision service cross those networks.

V. Conclusion

The energy consumption problem in the wireless industry is identified as a crucial problem for the sustainable growth of the ICT sector. As wireless access networks experience exponential growth worldwide, it is important to put energy efficiency as the first priority concern in design and development of next generation wireless access networks. Regarding LTE as an important standard for future wireless access networks, this paper provides an overview on recent energy saving efforts for the LTE system. The key energy consumption problems in a BS are identified and various solutions are briefly introduced. The initial performance study show the potential of those solutions to achieve energy saving. We identify key research problems in this area and propose promising research directions. All solutions following those directions will contribute to next generation green wireless access networks.

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