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Analysis of Energy-Efficient in Wireless Communication

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***Abstract*— Reducing energy consumption in wireless communications has attracted increasing attention recently. Since battery technology has not progressed as hastily as semiconductor technology, the power efficiency has become increasingly important in wireless networking, in addition to traditional quality and performance measures, such as throughput, bandwidth and fairness. In order to meet the growing mobile data demand, future wireless networks will be equipped with a multitude of access points (APs).In this paper, analysis of the energy - efficient consumption model, cross layer in energy efficient and the network resource management in energy efficient.**

***Keywords*— cross-layer optimization, energy efficiency, network design, wireless communications.**

I. INTRODUCTION

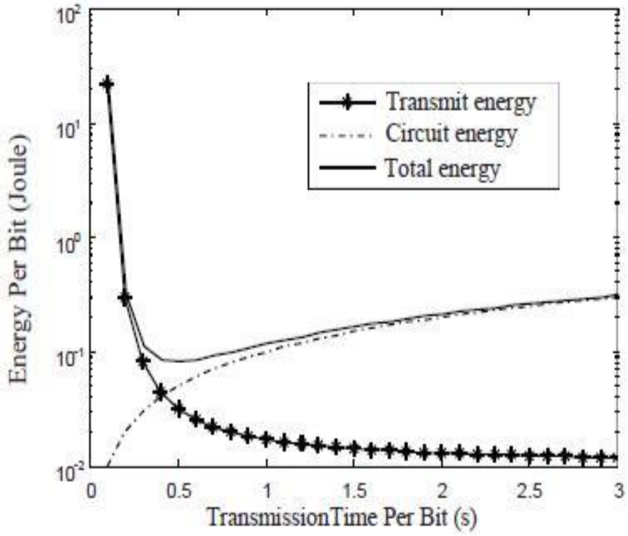
With the rapid and radical evolution of *information and communication technology* (ICT), corresponding energy consumption is also growing at a staggering rate [60]. Furthermore, it has been reported that mobile operators are already among the top energy consumers (for example, Telecom Italia is the second largest energy consumer in Italy [61]), and energy consumption of mobile networks is growing much faster than ICT on the whole [61]. Moreover, as the mass deployment of 3G systems in developing countries (like China and India) and later 4G systems worldwide occurs, the mobile communications will consume drastically more energy if no effective actions are taken.

The recent growth rate of wireless data exceeds both spectral efficiency improvements and availability of new wireless spectrum, and is therefore driving greater spatial reuse through a larger number of small cells and access points (APs) [57]–[59].

From Table I, it is clear that the high-efficiency PA, low-power circuit design and *digital signal processing* (DSP) technologies, adequate EE metric, advanced cooling systems and energy consumption models, cell-size deployment, various relay and cooperative communications, adaptive traffic pattern and load variation algorithms, and energy-efficient network resource management, as well as OFDM and MIMO techniques, are the highlights of energy-efficient wireless communications. However, since the energy-efficient hardware techniques and cooling systems are outside our research field, they are not included in this survey.

.II. ENERGY-EFFICIENT METRIC ENERGY CONSUMPTION MODELS

An adequate EE metric is primary importance in overall energy-efficient network design since it’s directly related to the optimized decisions across all the protocol layers. In this literature, several different EE metrics have been used. The most popular ’*bits-per-Joule*’, which is defined as the system throughput for unit-energy consumption. Some information theoretic results for energy-efficient communications at the link level, based on the bits-per-Joule metric, given in the [5]–[8], where as the transmit power limitation is considered as the primary constraint. It shows that the supremum channel capacity per unit energy can only be achieved by using an unlimited number of degrees of freedom per information bit (transmit with infinite bandwidth or with the longest duration). In the [9], bits-per-Joule capacity at the network level is analyzed, where it shows that the bits-per-Joule capacity increases with the number of nodes in the networks and implies that large-scale energy-limited sensor and adhoc networks may be only suitable for delay-tolerant data application. The bits-per-Joule metric is also widely used as the utility function in game-theoretic approaches for energy saving in wireless networks [10]–[13]. In the aforementioned research work, the energy consumption models only consider the transmit power associated with data transmission rate; however, the transmit power is only a part of the overall energy budget.



When the energy consumption of the other parts (e.g. circuit power consumption of the transceiver) is taken into account, the energy-efficient schemes discussed in [5]–[13] might not be appropriate. For example, the mathematical analysis in [14] shows that energy-efficient transmission by transmitting with the longest duration, is no longer the optimal approach. As an illustration, Fig.1 from [14] shows the tradeoff the overall EE between circuit energy and transmit energy. Based on the fact that for a given bit error probability, the *signal-to-noise-ratio* (SNR) per bit requirement increases with *M* for *M-ary quadrature amplitude modulation* (MQAM) and decreases with *M* for *M-ary frequency-shift keying* (MFSK),[SNR per bit is often denoted as $E_b/N0$, where E_b refers to the received energy per information bit, and $N0$ refers to the power spectral density of the noise] it is thought that MFSK is more energy efficient than MQAM [15]. However, it is shown in [16] that when the circuit power is considered it may no longer be true. The authors only show that when transmit power dominates the total power consumption, as for long-range applications, is MFSK more energy-efficient than MQAM; and, when the circuit power dominates the total power consumption, as for short-range applications, MQAM is more energy-efficient. It is also shown in [16] that by optimizing the transmission time and the modulation parameters, up to 80% energy savings is achievable compared with a non-optimized strategy for uncoded systems. Similarly, it is demonstrated in [17] that when circuit power is taken into account, there exists a Crossover in the transmission rate with respect to EE between MIMO and *single-input multiple-output* (SIMO). Below the crossover point, SIMO is more energy-efficient; above it, MIMO is more energy-efficient. In addition, an adaptive switching mechanism, between MIMO and SIMO, is proposed in [17] that can reduce the energy consumption by more than 50% compared with using MIMO under all conditions. In [18], it is shown that even when the energy consumption of the local information exchange for cooperation is considered, MIMO still out performs direct transmission as long as the transmission distances larger than a given threshold. In [19], a link-adaptive transmission scheme for MIMO-OFDM systems is proposed, which gives the maximizes EE in terms of bits-per-Joule using dynamic power allocation based on the circuit power consumption as well as the channel state. Obviously, the different methods for modeling the ”energy consumption” have significant impact on the bits-per-Joule metric. Therefore, it is important to set up a precise energy consumption model. There has been some work related to this area. The energy consumption models of macro cellular and microcellular base stations are investigated in [20]. In these models, the energy consumed at the base station with no traffic load, dubbed the ’*static energy part*’, and the ’*dynamic energy part*’, which depends on the traffic load, are added together to give the total energy

Table 1: Possible Solutions for Energy – Efficient Wireless Communications

Project Name	**Solutions**
Green Radio	**1. Energy Metrics & Models:** - Energy Communications consumption models **2. Energy-Efficient Hardware:** - Advanced power amplifier hardware integration & techniques - Maximize equipment and base station re-use **3. Energy-Efficient Architectures:** - Small cell vs. large deployment - Overlay source (microcell, picocell, femtocell) & multi-hop routing, relay & network coding and cooperative networking **4. Energy-Efficient Resource Management:** - MIMO vs. SISO with packet scheduling - Identification of the energy-efficient

	cooperative physical layer architecture using emerging information theory ideas to mitigate interference • Solar-powered relaying allocating resources to match the combined traffic and weather patterns
EARTH	**1. Energy-Efficient Analysis, Metrics and Targets:** • Analysis of the energy consumption life cycle by telecommunications products • Energy-efficient metrics on the system level **2. Energy-Efficient Architectures:** • Cell size optimization • Heterogeneous network deployment **3. Energy-Efficient Resource Management:** • Dynamic load adaptation and the transmission mode adaptation • Interference coordination, Cooperative scheduling, and joint power and the resource allocation • Multi-RAN (radio access network) coordination **4. Radio Technologies and Components:** • OFDM, MIMO, adaptive antennas and other advanced transmission techniques • Power scalable transceiver and power control on component, front end and system level
OPERA-Net	**1. Energy-Efficient Mobile Radio Access Network:** • Define key performance indicators for energy efficiency • Energy saving in base stations, network variations in traffic, cell breathing based on network loads, and sleep mode • Efficiency from the management of MAC, DC power, cooling system, etc. **2. Link Level:** • Optimization techniques for link-level energy efficiency (scalable MIMO-detection, fountain codes and amplitude modulation, scalable turbo-decoding) • Energy-aware device (terminals and infrastructure) design **3. Technology Enablers:** • Develop new high-efficiency power amplifier • Innovative energy recovering technique **4. Network Test Bed:** • Devices integration • Mobile radio access network’s end-to-end efficiency
eWin	**1. Energy-Efficient Architectures:** • Architectural designs for low-energy wireless access exploiting ”novel” tradeoffs between spectrum, service quality, and energy consumption • Infrastructure and novel networking paradigms for delay-tolerant services **2. Energy-Efficient Resource Management:** • Auto(re)-configuration of control software and networking resources, inresponsetochangesin infrastructure and demand • Radio resource management for competitive and cooperative heterogeneous environments

consumption in the base station. It’s found that the power consumption depends on the type of base station. In particularly, the energy consumption of a microcell base station mainly depends on the dynamic part (e.g., allocated transmit power and the number of allocated subcarriers). However, in macro cell base station, the energy consumption is dominated by the static part and does not significantly depend on the transmission parameters of each user. On the other hand, the definition of ”throughput” also affects the accuracy of the bits-per-Joule metric. We should not add all the transmitted data into the throughput, since not all of the transmitted data are real information bits. For example, the header required in different protocols, signaling information, destroyed packets, and duplicate packets all present overhead bits. The energy consumption of training sequences for channel estimation in fading channels is considered in [21], where it is shown that the optimal power allocation for pilot and data symbol in terms of EE can reduce transmit power consumption by 84.5% compared with optimal power allocation scheme for maximizing the capacity. In [13], throughput is defined as “goodput” – as the number of bits transmitted without error, to address this issue. Other research on the effect of protocol headers on energy consumption is 2TCP: Transmission Control Protocol, one of the core protocols of the Internet protocol suite.

1. Traditional energy-efficient technologies only consider the transmit power consumption and only make sense when the transmit power dominates the total energy consumption, such as for long-distance transmission [16], [18] and possibly for high data rate applications [17].

2. A holistic and system-wide EE metric is imperative. This EE metric should include all the energy consumption such as the transmission power, circuit power and signaling overhead in the entire network; and tradeoffs must be made between them such that the energy savings in one part would not be counteracted by increased energy consumption in another part. However, EE is not the only figure of merit for designing wireless networks. Spectral efficiency, deployment cost, network coverage and QoS requirements (such as transmission rate and delay) are also important ’metrics’ that should be seriously considered. A detailed analysis and discussion on the fundamental tradeoffs among these metrics such as *deployment efficiency* vs EE, *spectrum efficiency* vs EE, *bandwidth* vs *power*, and *delay* vs *power* can be found in [2].

III. CROSS LAYER SYSTEM MODEL

A. Topology and Access Scheme

We consider the uplink of a wireless network where nodes can be partitioned into groups, or clusters. We assume that each cluster has an access point, and that each node in the cluster is randomly placed in the neighborhood of the AP[52].Our model is general and can capture various network architectures such as heterogeneous networks, ad hoc networks, etc. [51], [53], [54]. The locations of all nodes in the cluster are uniformly distributed according to a Poisson point process (PPP) of density λ in a circular area of radius dc and centered in x, represented by b(x, dc), with $M = \lambda \Pi$ ${}_{2}$ the average number of nodes in each cluster. Let dc be the cluster radius and let x be the location of the AP. For ease of notation, we use $x_{h,i}$ to indicate the *i*-th AP, as well as its location. We will refer to the cluster centered around the origin as the representative cluster, and nodes located outside this cluster contribute to the interference. Outside the representative cluster b(0, dc), the parent process of APs xh,i follows a PPP with density λ h. Since the active nodes are uniformly distributed within the coverage area b(xh,i, dc) of the AP $x_{h,i}$ the total set of interfering nodes in uplink forms a Matern cluster process denoted by [55]. Each AP receives messages from all nodes in the uplink. We assume that the nodes use a strategy based on orthogonal frequency channels, where the available bandwidth is partitioned into a set of N multiple closely spaced subcarriers.3 Nodes use subsets of subcarriers, and this allows simultaneous data transmission from several nodes. Network management is then achieved by means of a *hybrid* signal processing scheme, where the nodes employ a MAC protocol that builds on a spectrum sensing functionality, and the APs employ multi-user decoding to resolve collisions arising from the random access protocol.

B. Energy Efficiency

Under a hybrid signal processing scheme, we can identify three main contributions to the energy consumption of the wireless network, namely (i) the sensing energy at all nodes, (ii) the transmission energy at all nodes, and (iii) the decoding energy at the APs. We consider the energy consumption of the entire network, therefore energy-efficiency tradeoffs will be such that the savings at the APs are not counteracted by increased consumption at the nodes, and vice versa [32]. The energy consumption in each cluster per subcarrier and per time slot can be modeled as

$$E = Es + Et + Ed \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where Es, Et, and Ed are the energy consumption due to sensing, transmission, and decoding, respectively. For each node that senses the spectrum occupation, the corresponding sensing energy consumption is proportional to the sensing power Ps and to the sensing time Ts. Similarly, the transmission energy Et of a node is proportional to the transmit power Pt and to the total transmission time of the node. The decoding energy consumption Ed is incurred at the AP during the decoding process, and it is assumed proportional to the decoding power Pd, to the time slot duration T , and to the total number of decoding attempts.

We denote by $x(\zeta)[\frac{bits}{s}]$ a spectral gain that accounts for the modulation scheme used and for the bandwidth of each subcarrier, where ζ is the SINR (signal-to-interference-plus noise ratio) decoding threshold. The throughput R of the wireless network is defined as the mean number of bits successfully transmitted to each AP per subcarrier and per time slot. Finally, the energy efficiency $\eta = \frac{R}{E}$ is defined as the number of bits successfully transmitted per joule of energy spent [56].

IV. ENERGY-EFFICIENT RADIO RESOURCE MANAGEMENT

Although the improved architecture can bring some benefits, the corresponding resource management is also in-dispensable to realize the green communication. For this reason, several technologies have been taken into account the energy efficient resource management, such as the switching off scheme, cell zooming, the using of renewable energy and so on. In traditional cellular networks, the operators deployed many BSs to cover the communication blind district and improve the communication quality. Although it really works sometimes, plenty energy has been wasted due to the low utilization of BSs. For this reason, many switching off schemes based on the variation of traffic load have been proposed in [33-40]. Except the common criterion presented above, the distance between the User Equipments (UEs) and the BSs mentioned in [33], the additional load increments transferred to the adjacent BSs considered in [35], the maximized coverage provided by active BSs and the coverage overlap of BSs adopted in [37,40] respectively are also the important criterions that should be taken into account. Besides the operation in BS, the switching off scheme can also be applied in relay networks. Although the transmitting power of RSs is much lower than BSs, RSs with lower utilization will also cause the energy wastage. In [41], the relays are dynamically switched off according to the variation of traffic loads. And in [42], the throughput and energy consumption are treated with the criterions simultaneously to decide which RSs should be switched off to improve EE of the net-work. As a power control technology, the cell zooming is used to satisfy the demand of traffic load in general, but can also increase EE of cellular networks. And in most instances, cell zooming is adopted as an assistant technology to improve the EE with other technologies. In [43,44], the authors put the low utilization BS into sleeping mode (operating with a low energy level) and cover the uncovered area by using cell zooming. And in [45,46], the cell zooming is combined with the switching off scheme to minimize the energy consumption. Except the technologies introduced above, the usage of renewable energy can also reduce the electric energy consumption more directly. In [47], a handover method is presented to guide the users to access the BSs powered by green energy. In [48], the authors propose a scheme to enable more users to be served by the green energy through cell zooming. In [49], the authors investigate a system model with BSs powered by the combination of electronic and renewable energy. And In [50], the authors combine the BS switching off scheme with hybrid power to further increase the EE. Although the renewable energy can reduce the electric energy consumption directly, the study of this aspect is beyond our research. For this reason, to our best know-ledge, the switching off scheme is considered as the most effective method to manage the resource within future networks. Moreover, the switching off scheme can also be combined with CoMP, cell zooming and/or other technologies to maintain a better coverage and improve the EE at the same time. Therefore, the joint switching off scheme needs further investigation. Energy-efficient radio resource management is one of the effective ways to reduce energy consumption of wireless systems. As mentioned in Table I, the list of all projects on green networks give effective radio resource management a prominent role. In this section, we mainly focus on energy saving under the low-traffic loads and exploiting QoS requirements for a different applications.

A. Energy Saving for Low Traffic Loads

Most current network dimensioning is peak-load oriented to satisfy the users' QoS requirements. In fact, much previous work [1], [4], [23]–[25] shows that the daily traffic loads at BSs vary widely over time and space. Therefore, a lot of energy wasted when the traffic load is low. Vendors and operators have already realized this problem and taken action. For instance, Alcatel-Lucent announced that a new feature of their software upgrades, called *dynamic power save* (DPS), can bring up to 27% power consumption reductions for BSs deployed by China Mobile [26]. Energy-saving solutions through cell-size breathing and sleep modes, based on the traffic loads, have been proposed by the OPERA-Net project [4].Optimal power-saving schemes using cell switch-off under a trapezoidal traffic pattern and a measured traffic pattern are analyzed in [27], where it is proved that a 25-30% energy saving is possible by simply switching off the active cells during the periods when their traffic is low. However, the effect of switch-off on coverage is not studied. In [25], a traffic-aware BS mode (active or sleeping) switching algorithm, based on the blocking probability requirement, is introduced. A minimum mode holding time is also suggested to avoid frequent BS mode switching. It is demonstrated that changing the holding time over a specified range will cause little performance change on either energy saving or blocking probability [25]. The impact of the mean and variance of the traffic load as well as the BS density on the energy saving strategy with BS switching is investigated in [23], which demonstrates that energy saving will increase with the BS density and the variance-to-mean ratio of the traffic load. In [28], some potential approaches to make energy consumption of BSs scale with the traffic load across time, frequency, and spatial domains are presented. It is also shown that the maximum energy-saving gain can be achieved by jointly reconfiguring the bandwidth and the number of antennas and carriers according to the traffic load [28]. Similar energy-saving solutions based on user load variations on the terminal side are introduced in [29]. In [30], multi-RAT (multiple radio access technologies) is proposed by the EARTH [3] project to take the advantage of the dynamic distribution of the traffic load among different radio access interfaces.

B. Service Differentiation

Energy saving should not only exploit the traffic load variations, but also the diversity of the QoS requirements. On the internet, the tradeoff between energy consumption and delay has been extensively studied. On the other hand, the cellular networks have only limited service types (mainly voice communications) were available in the early systems (1G, 2G systems), little has been done. However, as mentioned above, with the evolution of cellular systems and the popularity of smart phones, such as the iPhone, more and more diverse applications will appear in cellular networks. In particular, some applications, such as video conferencing, web-based seminars, and video games, require real-time service; and other applications, such as email, and downloading files for offline processing, are delay tolerant. Hence, it is beneficial to differentiate the types of traffic and make the energy consumption scale with the traffic type.

Recently, some researchers have exploited the service latency of applications to reduce the energy consumption in cellular networks. In [13], energy-efficient power and rate control with delay QoS constraints in CDMA-based systems using a game-theoretic approach is presented, where the delay constraint of a user is translated into a lower bound on the user's output SIR (signal-to-interference ratio) requirement, and then the Pareto-dominant equilibrium solution is derived.

The delay performance of users at the Nash equilibrium is also analyzed. Inspired by mobility-prediction-based transmission strategies, which are usually used in delay tolerant networks, a *store-carry-and-forward* (SCF), relay-aided cellular architecture is proposed in [31], [32]. In the SCF scheme, when the application data is not delay sensitive, a user can first transmit the data to a mobile relay (for example, a vehicle) which carries the message close to the BS, and then the mobile relay retransmits the data to the BS. Numerical results in [32] show that, for delay insensitive services, a factor of more than 30 in energy savings can be obtained by SCF compared with direct transmission. The delay-power tradeoff and some open issues on this problem are also introduced in [2].

C. Summary and Future Work

In general, the two main findings from the discussion above are:

1. The traffic loads at BSs vary widely over time and space [1], [4], [23]–[25], and load adaptive resource management (e.g. cell-size breathing [4], base station mode switching between active and sleeping [23], [25], [27], resource reconfiguring [26], [28]) can achieve significant energy saving.
2. Exploiting the diversity of QoS requirements for different applications can save a significant amount of energy (e.g. SCF transmission for delay tolerant applications in [31],[32]). Existing research has shown that energy-efficient radio resource management can provide significant energy savings.

However, several important issues are still open:

1. The collaboration between neighboring cells should be further studied since the cell mode switching changes the coverage and handoff issues. The effect of these changes on EE should be evaluated.
2. When the diversity of QoS requirements for different applications is exploited, a more general and practical QoS requirement model, as well as the fairness issues between users, should be considered. For instance, since both the channel condition and the traffic flow are time-varying in wireless networks, it is quite possible that a traffic flow has a higher transmission priority according to its QoS requirement, but the corresponding channel condition is bad. Thus, we should balance the EE gain based on the diversity of QoS requirements and the QoS requirements themselves.
3. Since most existing work only considers time-domain solutions (cell mode switching) for energy-efficient radio resource management, joint time-domain, frequency-domain (e.g. bandwidth allocation, cognitive radio and carrier aggregation) and spatial-domain (e.g. MIMO technology and directional antenna) solutions should be studied in the future.

V. CONCLUSIONS

Energy is one of the most critical resources for WSNs. Many factors can influence the energy consumption in wireless sensor networks. A lot of research is being done in this area. Previous research shows that optimized energy-efficient design (including network deployment, transmission scheme and resource management) could significantly reduce the energy consumption of the entire network. Nevertheless, current research results are still quite preliminary and many challenges remain.

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