

RECENT ADVANCES IN ENERGY-EFFICIENT NETWORKS AND THEIR APPLICATION IN 5G SYSTEMS

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ABSTRACT

This article provides an overview on research in energy-efficient wireless networks during the past decade and discusses its potential applications toward the fifth generation cellular systems. After analyzing the trade-off between spectrum efficiency and energy efficiency, various research results are summarized within a framework of energy-efficient resource allocation with optimization as a common tool. Then potential energy efficiency improving approaches in both physical layer and deployment aspects are provided. Finally, energy efficiency related open problems in massive multiple-input multiple-output, device-to-device communications, ultra dense networks, and other emerging technologies are identified.

INTRODUCTION

Even though study on energy-efficient communications can be dated back to at least two decades ago by information theorists, it became very active about 10 years ago. Recently, energy cost and its contribution to global carbon dioxide emission are emerging as major concerns, which is a severe problem for cellular networks. While the trend of radio access techniques is to cope with explosive growth of traffic loads and ever increasing demands on network capacity, the importance of energy efficiency (EE) for wireless networks has been realized.

EE measures the number of bits transmitted per joule of energy consumed. It incorporates the cost of energy consumed to achieve spectral efficiency (SE). In practical systems, spectrally-efficient techniques are not necessarily energy-efficient, and there may be a trade-off between SE and EE. There may also be trade-offs between EE and other measures [1], such as EE-delay and EE-deployment cost. In [2], a survey on SE, EE, and quality of service (QoS)-based user association, interference management, and resource allocation is provided for heterogeneous networks (HetNets). How to improve EE in the fifth generation (5G) cellular networks

without compromising the user experience becomes an important issue.

Recently, 5G cellular networks are becoming the most active research topic in wireless communications, as evidenced by many forums, research groups, and project consortiums pushing the research forward. In order to provide massive connections from various terminals, including not only smartphones but also machine-type communication devices with diverse QoS requirements, the 5G mobile network is required to have tremendous SE and EE improvement simultaneously. While increasing network capacity 1000-fold can be achieved by a large number of small cells, large-scale antennas, and much wider bandwidth in millimeter wave bands, reducing energy consumption at the same time is still very challenging [3]. As a result, SE, EE, and cost efficiency have been used as three obligatory 5G system evaluation metrics.

This article provides a comprehensive overview of research in energy-efficient communications and its potential applications in 5G networks. Different from [2], this article addresses the EE issues for 5G networks with new architectures. Specifically, in the next section, we first analyze the SE-EE relationship and then summarize various energy-efficient resource allocation issues from the perspective of optimization. Then we highlight potential EE improving approaches. Following that, some challenges toward energy-efficient 5G networks are identified, including EE in massive multiple-input multiple-output (MIMO), EE improvement by device-to-device (D2D) communications, and ultra dense networks (UDN). Finally, a conclusion is drawn in the final section.

ENERGY-EFFICIENT WIRELESS NETWORKS

Energy-efficient transmission originates from energy-constrained networks [4], such as wireless sensor networks, ad hoc networks, and satellite communications, where wireless devices are powered by batteries that are not rechargeable or hard to recharge, so energy consumption must be minimized. Since the development of

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Research areas	Motivations	Research focus and application scenarios
Information theory	Minimize energy per bit	Minimize transmit power in low SE region or in transmit power constrained systems
Sensor networks	Prolong the lifetime of the network	Minimize total energy consumption in low data rate, battery energy constrained systems (may not be rechargeable)
Uplink cellular systems	Prolong the standby time of the mobile device	Maximize the uplink SE to reduce the energy consumed at mobile devices, which is battery energy constrained
Downlink cellular systems and multi-cell networks	Reduce global CO ₂ emission and operation cost	Maximize the EE of the network under the QoS constraint of each user

Table 1. EE related research in wireless communications.

battery technology is much slower than the increase of energy consumption, mobile terminals in cellular systems must be energy-efficient. Especially with the recent explosively growing demand on mobile multimedia communications, the battery energy constraint has become a major concern for smartphones. This motivates optimization toward improving the EE of mobile devices. On the other hand, information and communications technology is playing a more and more important role in global greenhouse gas emission in the past several years, of which about 80 percent is consumed by base stations (BSs) in cellular networks. To reduce CO₂ emission and support sustainable development, resource allocation toward improving the EE of networks has drawn considerable attention.

In the early stage, EE has been studied from the perspective of information theory: energy-efficient communications focus on minimizing the transmission power only, which is reasonable when the transmission power is dominant, such as in long-range wireless communications. However, in short-range transmission, such as sensor networks and small cell cellular networks, the circuit power is comparable to the transmit power and cannot be ignored, which dramatically changes the way wireless networks are designed. For example, it has been shown in [4] that the traditional belief that a longer transmission duration reduces energy consumption may be misleading when the circuit power is considered. In short-range applications, the transmission power, which is directly related to the data rate, and the circuit power should be carefully balanced to achieve high EE. In Table 1, we list various related research areas in wireless communications.

THE SE-EE RELATIONSHIP

The objectives of radio resource allocation can be classified as user-oriented and network-oriented. The user-oriented measure reflects the interests of individual users, including the QoS requirement of a user and battery power consumption. The network-oriented measure reflects the usage of network resources and collective metrics for all users. SE and EE are from the network perspective, and depend on the channel characteristics and system settings. QoS, on the other hand, is from the user perspective,

and relies on the features of sources and diverse traffic demands.

SE stems from information theory, and concerns the capability for transmission without considering QoS and cost. The fundamental bound on data transmission rate is the channel capacity, and is a function of bandwidth and power. It has played an important role in defining the goal of spectral-efficient design. EE by nature accounts for the energy consumption to support the required data transmission rate. To optimize network resource usage considering both SE and EE, the fundamental bounds on the SE-EE relationship as a function of various system resources, such as transmit power, transmission duration, bandwidth, number of BSs, and numbers of transmit and receive antennas, can shed light on how we should develop energy-efficient techniques.

Existing studies on the SE-EE relationship can be divided into two categories. One is to find the relationship directly from capacity formulas, considering either ergodic capacity with statistics of channel state information at the transmitter (CSIT) or instantaneous capacity with instantaneous CSIT. To circumvent the difficulty of finding a closed-form expression, approximation is often used. For example, an approximate SE-EE relationship has been derived for MIMO systems by using heuristic curve fitting in [5], where ergodic capacity is considered. Sometimes, extreme case analysis can help find a nice expression. For example, a simple closed-form expression for massive MIMO systems has been derived, which provides interesting insight [3].

Another way to investigate the SE-EE relationship is to maximize the instantaneous EE, usually defined as the ratio of instantaneous throughput to the total power consumption, for a given SE. In [6], a framework on the SE-EE relationship for downlink orthogonal frequency-division multiple access (OFDMA) systems has been established, where the QoS constraint on the minimal instantaneous rate requirement of each user and fairness among multiple users are imposed. Besides analyzing how the optimal EE changes with the required SE and the maximal value of the optimal EE in the SE feasible region, how the EE of the system changes with the QoS requirement of each user has also been

investigated. Although it is hard to find the closed-form expression for the SE-EE relationship in this situation, the basic properties of the SE-EE relationship are demonstrated.

Furthermore, tight upper and lower bounds on the SE-EE curve for general scenarios have been found. To understand how the EE changes with the SE for various systems, the global maximum EE without accounting for the QoS requirements is also obtained, which corresponds to elastic traffic.

In general, the SE-EE relationship depends on the relative values of the transmit power and circuit power. If a system operates in the circuit power dominated regime, maximizing SE can also improve EE. If a system operates in the transmit power dominated regime, such as when the distance between a BS and a user is large, in contrast, there will be a trade-off between SE and EE. Nonetheless, even in the SE-EE win-win region, a high SE technique does not automatically provide maximal EE.

The SE-EE relationship and the corresponding optimal transmission strategy also depend on the specific network. In interference-limited networks, it has been shown that EE is much more sensitive to the transmit power than SE, and increasing transmit power beyond its optimal value for EE brings little SE gain but hurts EE significantly. The strategy maximizing the sum EE of multiple users is also beneficial to the sum SE and exhibits an improved SE-EE trade-off.

Besides SE-EE trade-off, there are other EE related trade-offs, such as trade-offs between EE and delay or deployment cost, which were investigated in [1].

ENERGY-EFFICIENT RESOURCE ALLOCATION

Since energy is directly related to the expenditure in operating a communication system, while throughput brings revenue, a basic principle of energy-efficient optimization is to maximize the EE without compromising the user experience or reducing the throughput of networks. To this end, the allocated resources should adapt to the required performance instead of the worst case scenarios.

Due to ubiquitous applications of real-time services, such as video streaming, online gaming, and mobile computing, which are all delay-sensitive and power consuming, spectrum/energy-efficient transmission subject to QoS requirements over wireless channels is becoming increasingly important. To address these three performance metrics for resource allocation, one method is to maximize the EE of the network under the QoS constraint imposed by the traffic. The resource allocation in this case can also be formulated as some sort of multi-criteria optimization. In the following, we discuss four key elements in optimization: objective functions, constraints, variables, and algorithms in energy-efficient related research.

Optimization Objective Functions: There are various EE related metrics, depending on the concerned system, knowledge of channels, and the purpose of optimization. For instance, a network may be either coverage-limited or capacity-limited, single-cell or multi-cell, and downlink or uplink.

For systems deployed in rural areas, coverage is a critical issue, and EE is measured as the ratio of average power consumption to the coverage area of the network. For systems in urban areas, the traffic load is often high, and a commonly used metric to evaluate EE is the ratio of the overall number of bits transmitted to the energy consumed at a certain period of time. For single-cell downlink transmission, the amount of data transmitted and energy consumed are from one BS. For multi-cell downlink transmission with a central unit to coordinate the transmission, the EE is the aggregated data from multiple BSs for multiple users to the energy consumed by the BSs, while the network EE is the sum of the EE of each user for interference networks. For uplink transmission, the amount of information transmitted and energy consumption are from each user if battery energy is a concern, while the information is from all users, and the energy consumption is from both BS and users if reducing CO₂ emission is the design goal. If CSIT is assumed, or equivalently assuming static channels, instantaneous EE can be used as the objective function. If only statistical channel information is available, EE defined as the ratio of the average throughput to the average power is more appropriate.

Another objective function often used is overall energy consumption. It should be noted that the objective of minimizing energy consumption is usually different from maximizing EE, which depends on the considered QoS constraint.

An alternative metric for optimization is to achieve an SE-EE trade-off. There is no doubt that such an optimization problem is useful for finding the Pareto optimal transmit policies. Nonetheless, as previously discussed, only if elastic traffic is considered and a system operates in transmit power dominant region will there be an SE-EE trade-off. Moreover, implicit assumptions behind achieving the SE-EE Pareto optimal are very heavy traffic load and full buffer.

Optimization Constraints: Different services need different QoS provision, for example, in terms of data rate, delay, bit error rate, and fairness. It is clear that the imposed constraints depend on the considered traffic models (e.g., real-time or best effort service, full buffer or not). For real-time traffic without the full buffer assumption, the QoS constraints of the users are usually characterized as the average source rate and an upper bound on the average delay, where the delay includes both transmission and queuing delays. For delay-sensitive traffic, a more accurate constraint should be a delay bound and its violation probability. For easy optimization while capturing the essence of the problem, these constraints often translate to a fixed rate constraint or minimal acceptable rate requirement of each user. Such a simplification is appropriate when the arrival rate of the source and transmission rate of the system are constant. Alternatively, the constraints on the average rate over time can be employed, which lead to larger energy savings compared to the instantaneous rate constraints since they provide the flexibility to dynamically allocate resources over the fading channels. For non-real-time traffic, such as best effort or elas-

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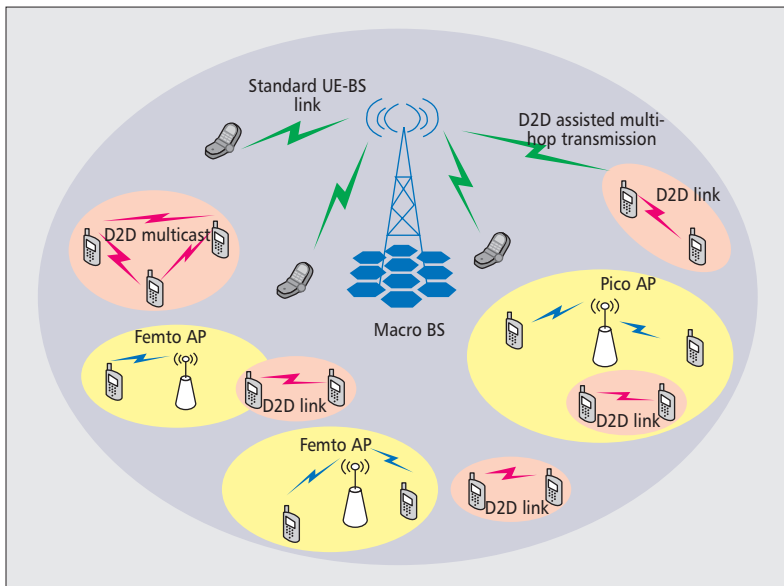


Figure 1. D2D communications in HetNets.

tic traffic with a low demand on latency, there is either no constraint or only a minimal throughput constraint, which can be viewed as a special case of those for real-time traffic.

Optimization Variables: It is obvious that the variables to be optimized largely depend on the concerned system setting. Besides those SE related variables, extra degrees of freedom for improving EE include BS sleeping, antenna closing, the overall transmit power allocation, and bandwidth scaling.

For instance, for multi-user multi-antenna systems, scheduling, antenna closing, and precoding can be optimized. For multi-cell networks, BS sleeping/idling and user access/scheduling can further be jointly designed. In addition, the resources allocated to channel estimation of various systems can also be optimized.

Optimization Algorithms: The EE maximization problem belongs to a class of optimization problems called fractional programs, where the objective function is a ratio of two real-valued functions [7]. When both the numerator and the denominator are differentiable (e.g., power allocation in a noise-limited network), EE is pseudoconcave, the optimal solution can be found from the Karush-Kuhn-Tucker (KKT) conditions and efficient algorithms, such as multi-level water-filling or bi-section algorithms. When the optimization variables are discrete (e.g., subcarrier assignment, antenna configuration, and BS sleeping), different layers of optimization algorithms are often used to optimize the discrete and continual variables, respectively.

ENERGY EFFICIENCY IN NEW TECHNIQUES AND DEPLOYMENT

To handle the exponential growth of mobile data traffic while alleviating the huge cost of infrastructure investment, D2D communications,

massive MIMO, and small cells have been proposed for Third Generation Partnership Project (3GPP) Long Term Evolution Advanced (LTE-Advanced) networks. In this section, we introduce current energy-efficient design in these systems.

DEVICE-TO-DEVICE COMMUNICATIONS

With the growing trend of proximity-based applications, such as peer-to-peer file sharing and local multicasting and advertising, D2D communications have been proposed to improve local service flexibility and network throughput, and to support public safety service in case of lack of network coverage in 3GPP LTE-Advanced. Figure 1 illustrates D2D communications in HetNets. In D2D communications, proximity users in cellular networks can transmit data directly to each other without going through the BS. Due to physical proximity, D2D communications can potentially provide proximity gain, reuse gain, and hop gain. Thus, D2D communications can significantly improve network SE and device EE.

Furthermore, D2D communications can provide more freedom for D2D users, as they can transmit data in three modes:

- *Dedicated mode:* D2D users directly transmit data by using the orthogonal resource of regular cellular users.
- *Reusing mode:* D2D users directly transmit data by reusing the resource of cellular users.
- *Cellular mode:* D2D users are treated as regular cellular users and communicate with each other through the BS in the standard way.

Through proper mode selection, EE of both devices and the network can be significantly improved. In [8], energy-efficient mode selection and power allocation was investigated. Substantial EE gain has been shown compared to traditional transmission without D2D [8].

MASSIVE MIMO

Traditional MIMO can obtain array gain, spatial diversity, and/or spatial multiplexing gains and improve EE. By deploying a much larger number of antennas at the BS than traditional MIMO, large-scale, or massive, MIMO, is regarded as one cost-effective technique for 5G networks [9]. In a massive MIMO system, the BS can communicate with multiple users simultaneously in the same frequency band, so high multiplexing gain as well as high array gain can be achieved at the same time. Massive MIMO systems can not only provide high SE, but also may improve EE.

A power scaling law in massive MIMO systems was revealed in [10]. When the number of antennas at the BS is much larger than that of users, channel vectors for different users are asymptotically orthogonal. In this case, simple linear precoders, such as matched-filter and zero-forcing, can be used to achieve the capacity asymptotically. The transmit power is scaled down by the number of antennas at the BS to achieve the same data rate as single-antenna systems when perfect CSIT is known at the BS. Besides the power scaling law, the EE of the massive MIMO systems has also been studied. From [10], the EE decreases with the increase of the SE with perfect CSIT. With imperfect CSIT,

the EE increases with the SE at the low power region and decreases with the SE at the high power region.

When circuit power is considered, massive MIMO equipped with more RF chains will consume considerable circuit power, which may lead to severe EE reduction. To improve the EE of the system, some antennas at the BS can be turned off, which is very similar to traditional MIMO. Alternatively, a hybrid analog and digital beamforming RF structure can be applied to balance the circuit power and transmit power, where multiple antennas connected with one RF chain form analog beamforming providing the array gain, and multiple groups of analog beams form digital beamforming providing the multiplexing gain [3].

SMALL CELLS

A small cell is formed by low-power and low-cost BSs, such as micro-, pico-, and femto-BSs. It can be densely deployed to provide high data rates. With an improved frequency reuse factor, a small cell is able to enhance SE significantly. At the same time, with reduced distance between the user and the BS, the required transmit power to overcome path loss, fading, and noise is also reduced, especially for indoor environments. As a result, both uplink and downlink EE can be improved [11]. Recently, energy-efficient inter-frequency small cell discovery techniques were proposed for HetNets in [11]. It requires minimal changes in the current 3GPP standards, but can save up to 99 percent of users' battery power consumption. The trade-off between traffic offloading from the macrocell and the energy consumption of the small cells can be implemented through a distributed BS sleeping strategy. In [2], a system framework of cooperative HetNets is presented for 5G systems, aimed at balancing the SE, EE, and QoS.

Most of the existing work on this topic focuses on data signal transmission in cellular networks, and little is known about the impact of signaling in EE. The concept of separating the control signals and data signals was proposed in a hyper-cellular network [12] for more energy-efficient and flexible radio access. This concept has been investigated for the LTE-Advanced networks [13] and 5G networks [3]. Furthermore, since small cells in 5G networks will be much denser than in 4G networks for hotspot coverage, interference management, while considering the SE and EE target, will be a challenging issue.

CHALLENGES IN ENERGY-EFFICIENT 5G NETWORKS

In 5G networks, energy consumption should be minimized at every level and stage of communications from a perspective of life cycle assessment. To this end, we need to rethink the ultimate goal of future wireless networks. Along with many emerging applications beyond voice communications and new usage models, the goal of 5G networks is no longer just transmitting as high data rate as possible, but satisfying a variety of users' needs in a more energy-efficient man-

ner. We need to identify where energy can be further saved and what available information in the network can be exploited. For instance, it may be possible to remove the redundant transmission generated from multiple copies of the same content (e.g., a popular video) by using multicast transmission or distributed caching at the nearest BS to users, or by D2D communications among a group of users. Context information, such as the moving direction and surrounding environment of a mobile terminal, can also be exploited. The new network architecture incorporating caching proposed in [14] will provide new opportunities to improve the utilization efficiency of both spectrum and energy.

RETHINKING THE DEFINITION OF EE

In the previous study, EE is defined as the ratio of data rate to power consumption. However, in the EARTH project, both the *power per area unit* and *energy per bit energy consumption* have been used as metrics for system-level evaluation, which is often called network EE. If we take into account the users' quality of experience (QoE) and various signaling to support the diverse services, which are suggested as major concerns of 5G networks, EE should be redefined. Therefore, the following two problems need to be considered:

- *Net EE*: The *network EE* should be defined as the ratio of *net throughput* to the total power consumed in the network subject to the QoE of each user. In the previous work, the control overhead to ensure link reliability has been ignored. In future study, we should redefine *optimization objective functions* according to the *net EE*.
- *End-to-end delay*: An important feature of QoE is end-to-end delay. However, little is known on how to model EE with various delay constraints, although there have been some related works to discuss the EE-delay trade-off.

EE FOR NEW NETWORK ARCHITECTURE AND WAVEFORMS

5G networks will support multiple radio access technologies for co-site deployment, which provides a potential for energy saving. The cloud radio access network (C-RAN) [3], which was first introduced by the China Mobile Research Institute in 2010, is a new radio access architecture for future mobile network infrastructure. With such a new architecture, much higher utilization efficiency of processing resources can be achieved by sharing the baseband unit pool among a large number of cells, the power consumed for air conditioners can be significantly cut down by reducing the number of sites, and the power for transmission can be reduced due to the short distance between the users and a remote radio head [2]. By using a virtual baseband transceiver switching pool, multi-cell cooperative baseband signal processing, and dynamic cell load balancing, C-RAN has been verified to be more energy-efficient than conventional RAN in field trials [3]. However, to improve the EE of the whole network, there are still some open problems.

A hybrid analog and digital beamforming RF structure can be applied to balance the circuit power and transmit power, where multiple antennas connected with one RF chain form analog beamforming providing the array gain, and multiple groups of analog beams form digital beamforming providing the multiplexing gain

Massive MIMO is considered a potential candidate for physical layer techniques, particularly for millimeter wave bands in 5G networks. However, different power consumption models at various mmWave bands present one basic challenge from the EE point of view: how to design EE improving scheme with massive MIMO?

Green Energy Supply: With green and recycled energy supply, new types of cellular BSs have been put into field trials. One challenging problem is to optimize EE systematically under the constraints of energy harvesting capability, on-grid energy utilizing efficiency, and deployment costs.

EE Optimized 5G Waveforms and Multiple-Access Techniques: Currently, various advanced multi-carrier waveforms, such as filter bank multi-carrier, and new multiple-access techniques, such as non-orthogonal multiple access and sparse code multiple access, have been proposed toward 5G systems. However, the EE problem needs further investigation.

EE IN MASSIVE MIMO

Massive MIMO is considered a potential candidate for physical layer techniques, particularly for millimeter-wave bands in 5G networks. However, different power consumption models at various mmWave bands present one basic challenge from the EE point of view: designing an EE improving scheme with massive MIMO. To fully understand the EE performance of massive MIMO systems toward 5G networks, more work needs to be done.

Power Consumption Model and Hardware Impairment: An adequate energy consumption model is of primary importance in overall energy-efficient network design since it is directly related to the objective functions. Since the frequency bands decide the power model of radio frequency front-end devices, it is hard to measure and model the EE of a massive MIMO system. Moreover, it is still an open problem to evaluate the impact of the hardware impairment on EE in massive MIMO systems.

EE of Massive MIMO Systems in HetNets: Given an area, it can be covered by a massive MIMO cell or a set of small cells. From the perspective of EE, the deployment of massive MIMO and HetNets for the same coverage is still being debated. Sleep mode control in HetNets can provide more flexible and higher EE for a large number of small cells, while a massive MIMO cell performs better than a small number of small cells due to its large array gain. Thus, energy-efficient massive MIMO systems in HetNets are worth further study.

D2D COMMUNICATIONS AND ULTRA DENSE NETWORKS

Existing research on D2D communications has shown great potential for 5G networks to improve both EE and SE. It leads to a trend toward the UDN [15]. However, several important issues, such as the trade-off between deployment cost and EE, are still open.

Energy-Efficient D2D Assisted Small Cell Deployment — Through D2D communications, users can be naturally adopted as relays, thus supporting multi-hop transmission between a user and a BS. Thus, D2D transmission may be established, and helps reduce the cost and size of BSs. In addition, with the help of rich D2D transmission in

the cell, the density/amount of heterogeneous BSs may be further decreased. It is worth investigating the throughput and coverage potential and impact of D2D transmission on small cell deployment in HetNets, and developing cost-efficient strategies to optimize the deployment.

Energy-Efficient D2D Spectrum Sensing: To deal with possible interference among D2D links, and between cellular and D2D links, conventional techniques would require significant signaling overhead, which sometimes undermines the advantage of introducing D2D communications. Enhanced with cognitive radio (CR) technology, user equipment can identify the portion of the licensed spectrum that is unused locally through spectrum sensing and opportunistically reuse the resource for D2D communications without introducing interference or additional signaling overhead to the existing cellular network. However, to ensure the advantage brought by CR technology, efficient spectrum sensing and sharing are necessary.

Energy-Efficient Resource Allocation in a Multi-Cell Scenario: Most existing work on energy-efficient resource allocation for D2D communications focuses on the single-cell scenario. In the multi-cell scenario, resource allocation is much more complicated as coordination between the neighboring BSs is needed to deal with the channel feedback, mobility management, and handover issues. However, compared to single-cell D2D communications, the multi-cell scenario is more beneficial since it may reduce energy consumption more, especially when two users are located at the cell edge of their own cells.

CONCLUSIONS

This article has presented a comprehensive survey on recent advances in EE wireless networks in the past decade and identified emerging challenges for potential applications in 5G cellular networks. The methodology in analyzing the SE-EE relationship has been summarized, and energy-efficient resource allocation has been addressed from the optimization perspective. Many open issues in designing energy-efficient 5G systems, such as massive MIMO, D2D, and UDN, have been provided.

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