IEEE Wireless Communications, April 2015, Vol. 22, No. 2, pp. 145-151

# Recent Advance in Energy-Efficient Networks and Its Application in 5G Systems

Gang Wu, Chenyang Yang, Shaoqian Li, and Gefforey Ye Li

*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 (5G) cellular systems. After analyzing the tradeoff between spectrum efficiency and energy efficiency (EE), various research results are summarized into a framework of energy-efficient resource allocation with optimization as a common tool. Then, potential EE improving approaches in both physical layer and deployment aspects are provided. Finally, EE related open problems in massive multiple-input multiple-output, device-to-device communications, ultra dense networks, and other emerging technologies, are identified.**

*Index Terms*—**Energy efficiency, spectrum efficiency, cellular networks, resource allocation, 5G wireless systems**

## I. INTRODUCTION

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

EE measures the number of bits transmitted every joule of energy consumed. It incorporates the cost of energy consumed to achieve spectral efficiency (SE). In practical systems, spectral-efficient techniques are not necessarily energy-efficient and there may exist a tradeoff between SE and EE. There may also exist tradeoffs between EE and other measures [1], such as EE-delay tradeoff and EE-deployment cost. In [3], a survey on SE, EE and 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 forward the research. In order to provide massive connections from various terminals, including not only smart phones but also machine-type communication devices with diverse quality-of-service (QoS) requirements, the 5G mobile networks is required to have tremendous SE and EE improvement simultaneously. While increasing 1000-fold of network capacity 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 [2]. As a result, SE, EE, and cost efficiency have been used as three obligator 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 [3], this article addresses the EE issues for 5G networks with new architectures. Specifically, in Section II, we first analyze the SE-EE relationship and then summarize various energy-efficient resource allocation issues from the perspective of optimization. In Section III, we highlight potential EE improving approaches. In Section IV, some challenges toward energy-efficient 5G networks are identified, including EE in massive multiple-input multiple-output (MIMO), EE improving by device-to-device (D2D) communications, and ultra dense networks (UDN). Finally, a conclusion is drawn in Section IV.

## II. 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 be recharged so that energy consumption must

G. Wu and S. Li are with National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731 China. e-mail: {wugang99,lsq}@uestc.edu.cn

C. Yang is with the School of Electronics and Information Engineering, Beihang University, Beijing, 100191, China. e-mail: cyyang@buaa.edu.cn

G. Y. Li is with Department of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, 30332 USA. e-mail: liye@ece.gatech.edu

be minimized. Since the development of battery technology is much slower than the increase of energy consumption, mobile terminals in cellular systems must be energy-efficient. Especially with the recent explosive growing demand on mobile multimedia communications, battery energy constraint has become a major concern for smart phones. This motivates optimization toward improving the EE of the 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 $CO_2$ emission and support sustainable development, resource allocation towards improving the EE of the 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 it can not be ignored, which changes the way to design wireless networks dramatically. 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 I, we have listed various related research in wireless communications.

### A. SE-EE Relationship

The objectives of radio resource allocation can be classified as user-oriented or network-oriented. The user-oriented measure reflects the interests of individual users, including 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 network perspective and depend on the channel characteristics and system settings. QoS, on the other hand, is from user perspective and relies on the feature of sources and diverse traffic demands.

SE stems from information theory, 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 in nature has accounted 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, numbers of transmit and receive antennas, can shed light upon on how we should develop energy-efficient techniques.

Existing studies on 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 to find a closed-form expression, approximation is often used. For example, an approximated 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 an interesting insight [2].

Another way to investigate the SE-EE relation 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 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, it has also been investigated how the EE of the system changes with the QoS requirement of each user. Though it is hard to find the closed-form expression for the SE-EE relation in this situation, the basic properties of SE-EE relation are demonstrated. Furthermore, a 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 relation depends on the relative values of the transmit power and the 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 BS and user is large, by contrast, there will be a tradeoff 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 relation and the corresponding optimal transmission strategy also depend on 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 tradeoff.

Besides SE-EE tradeoff, there are other EE related tradeoffs, such as tradeoffs between EE and delay or deployment cost, which have been investigated in [1].

### B. 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 EE of the network under the QoS constraint imposed by the traffic. The resource allocation in this case can be also formulated as some sorts of multi-criteria optimization. In the following, we will discuss four key elements in optimization, objective functions, constraints, variables, and algorithms in energy-efficient related research.

*1) Optimization objective functions:* There exist various EE related metrics, depending on the concerned system, knowledge of channels, and the purpose of the optimization. For instance, a network may be either coverage-limited or capacity-limited, single cell or multi-cell, and downlink or uplink. For the systems deployed in the rural areas, the coverage is a critical issue and the EE is measured as the ratio of average power consumption to the coverage area of the network. For the systems in the urban areas, the traffic load is often high and a commonly used metric to evaluate the EE is the ratio of the overall number of bits transmitted to the energy consumed in a certain period of time. For single cell downlink transmission, the amount of data transmitted and the 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 the battery energy is a concern while the information is from all users and the energy consumption is from both BS and users if reducing carbon dioxide 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, the EE defined as the ratio of the average throughput to the average power is more appropriate.

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

An alternative metric for optimization is to achieve a SE-EE tradeoff. 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, there will exist the SE-EE tradeoff. Moreover, implicit assumptions behind achieving the SE-EE *Pareto* optimal are very heavy traffic load and full buffer.

*2) Optimization constraints:* Different services need different QoS provision, e.g., 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 the 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 meanwhile 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 as compared to the instantaneous rate constraints since it provides the flexibility to dynamically allocate resources over the fading channels. For the non-real-time traffic, such as best effort or elastic traffic with a low demand on latency, there is either no constraint or only with a minimal throughput constraint, which can be viewed as a special case of those for the real-time traffic.

*3) Optimization variables:* It is obvious that the variables to be optimized largely depend on the concerned system setting. Besides those SE related variables, extra degree of freedoms 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 be further jointly designed. In addition, the resources allocated to channel estimation of various systems can be also optimized.

*4) Optimization algorithms:* 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, then the optimal solution can be found from the Karush-Kuhn-Tucker (KK-T) 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 continues variables, respectively.

## III. ENERGY EFFICIENCY IN NEW TECHNIQUES AND DEPLOYMENT

To handle the exponential growth of mobile data traffic while alleviate the huge cost of infrastructure investment, D2D communications, massive MIMO, and small cells have been proposed for the Long Term Evolution Advanced (LTE-Advanced) networks. In this section, we will introduce the current energy-efficient design in these systems.

### A. Device-to-Device Communications

With the growing trend for 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. Fig. 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 the 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 significant improved. In [8], energy-efficient mode selection and power allocation has been investigated. Substantial EE gain has been shown compared with the traditional transmission without D2D [8] .

### B. 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 MIMO, or massive MIMO, is regarded as one of cost-effective techniques for the 5G networks [9]. In a massive MIMO system, the BS can communicate with multiple users simultaneously in the same frequency band, high multiplexing gain as well as high array gain can be achieved at the same time. Massive MIMO systems not only can provide high SE, but also may improve EE.

A power scaling law in the massive MIMO systems has been 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 been also 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 it decreases with the SE at the high power region.

When the circuit power is considered, massive MIMO equipped with more radio frequency (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 the 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 [2].

### C. Small Cells

Small cell is with 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, small cell is able to enhance SE significantly. At the same time, with a reduced distance between the user and the BS, the required transmit power to overcome path loss, fading, and noise is also reduced, especially for the indoor environments. As a result, both uplink and downlink EEs can be improved [11]. Recently, energy-efficient inter-frequency small cell discovery techniques have been proposed for HetNets in [11]. It requires minimal changes in the current 3GPP standards, however can save up to 99 % users' battery power consumption. The tradeoff between traffic offloading from the macro-cell and the energy consumption of the small cells can be implemented through distributed BS sleeping strategy. In [3], a system framework of cooperative HetNets is presented for 5G systems, aiming at balancing the SE, EE, and QoS.

Most of the existing works in this topic focus 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 the data signals, has been proposed in *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 [2]. Furthermore, since small cells in 5G networks will be much denser than that in the 4G networks for hotspot coverage, interference management, while considering the SE and EE target, will be a challenging issue.

## IV. CHALLENGES IN ENERGY-EFFICIENT 5G NETWORKS

In 5G networks, the energy consumption should be minimized in every level and every stage of communications from a perspective of life-cycle-assessment. To this end, we need rethinking what is the ultimate goal of the 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 data as high data rate as possible, but satisfying a variety of users' needs in a more energy-efficient manner. We need to identify where the 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 catching 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.

### A. Rethinking the Definition of EE

In the previous study, EE is defined as the ratio of the data rate to the power consumption. However, in the EARTH project, both the *power per area unit* and the *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 re-defined. 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 the link reliability has been ignored. In the future study, we should redefine *optimization objective functions* according to the *net EE*.
- *End-to-end delay:* An important feature of QoE is the end-to-end delay. However, little is known on how to model the EE with various delay constraints although there have been some related works to discuss the EE-delay tradeoff.

### B. EE for New Network Architecture and Waveforms

5G networks will support multiple radio access technology for co-site deployment, which provides a potential for energy saving. The cloud radio access network (C-RAN) [2], which was first introduced by 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 will be reduced due to the short distance between the users and remote radio head [3]. By using 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 by field trials [2]. However, as to improve the EE of the whole network, there are still some open problems.

- *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 harvest capability, on-grid energy utilizing efficiency, and deployment costs.
- *EE optimized 5G waveforms and multiple-access techniques:* Currently, various advanced mutlicarrier 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.

### C. EE in Massive MIMO

Massive MIMO is considered as a potential candidate for physical layer techniques, particularly for millimeter wave bands in 5G networks. However, different power consumption model at various mmWave bands provide one basic challenges from EE point of view: how to design EE improving scheme with massive MIMO? To fully understand the EE performance of the 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 primarily 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 the 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 perspective of EE, the deployment of massive MIMO and HetNets for the same coverage is still in debate. Sleep mode control in HetNets can provide more flexible and higher EE for a large number of small cells while the massive MIMO cell performs better than that of small number of small cells owing to its large array gain. Thus, energy-efficient massive MIMO systems in HetNets are worth of further study.

### D. D2D Communications and Ultra Dense Networks:

Existing research on D2D communications has shown a great potential for 5G networks to improve both EE and SE. It leads to a trend for the UDN [15]. However, several important issues, such as the tradeoff 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 inherently support 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 to investigate the throughput and coverage potential and impact of D2D transmission on the 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 multi-cell scenario*: Most existing works on energy-efficient resource allocation for D2D communications focus on the single cell scenario. In multi-cell scenario, resource allocation is much more complicated as the coordination between the neighboring BSs is needed to deal with the channel feedback, mobility management, and handover issues. However, compared with 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.

## V. 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.

## ACKNOWLEDGMENT

This work was supported in part by National High-Tech R&D Program (863 program) under Grant 2012AA011402, National Basic Research Program of China under Grant 2012CB316003, National Natural Science Foundation of China under Grant 61120106002 and 61471100, and by China Mobile Research Institute under Grant 2013346.

## REFERENCES

[1] Y. Chen, S. Zhang, S. Xu, and G. Li, "Fundamental trade-offs on green wireless networks," *IEEE Commun. Mag.*, vol. 49, no. 6, Jun. 2011, pp. 30–37.

[2] C.-L. I, C. Rowell, S. Han, Z. Xu, G. Li, and Z. Pan, "Toward green and soft: A 5G perspective," *IEEE Comm. Mag.*, vol. 52, no. 2, Feb. 2014, pp. 66–73.

[3] R. Q. Hu and Y. Qian, "An energy efficient and spectrum efficient wireless heterogeneous network framework for 5G systems", *IEEE Commun. Mag.*, vol. 52, no. 5, May 2014, pp. 94–101.

[4] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-constrained modulation optimization," *IEEE Trans. Wireless Commun.*, vol. 4, no. 5, Sept. 2005, pp. 2349–2360.

[5] F. Heliot, M. A. Imran, and R. Tafazolli, "On the energy efficiency spectral efficiency trade-off over the MIMO Rayleigh fading channel," *IEEE Trans. Commun.*, vol. 60, no. 5, May 2012, pp. 1345–1356.

[6] C. Xiong, G. Y. Li, S. Zhang, et. al., "Energy- and spectral-efficiency tradeoff in downlink OFDMA networks," *IEEE Trans. Wireless Commun.*, vol. 10 , no. 11, Nov. 2011, pp. 3874–3886.

[7] C. Isheden, Z. Chong, E. Jorswieck, and G. Fettweis, "Framework for link level energy effciency optimization with informed transmitter," *IEEE Trans. Wireless Commun.*, vol. 11, no. 8, Aug. 2012, pp. 2946–2957.

[8] D. Wu, J. Wang, R. Q. Hu, et. al., "Energy-efficient resource sharing for mobile device-to-device multimedia communications," *IEEE Trans. Veh. Technol.*, vol. 63, no. 5, Jun. 2014, pp. 2093–2103.

[9] J. G. Andrews, S. Buzzi, W. Choi, et. al., "What will 5G be?" *IEEE J. Select. Areas Commun.*, vol. 32, no. 6, Jun. 2014, pp. 1065–1082.

[10] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, "Energy and spectral efficiency of very large multiuser MIMO systems," *IEEE Trans. Commun.*, vol. 61, Apr. 2013, pp. 1436–1449.

[11] A. Prasad, O. Tirkkonen, P. Lunden, et. al., "Energy-efficient inter-frequency small cell discovery techniques for LTE-advanced heterogeneous network deployments," *IEEE Commun. Mag.*, vol. 51, no. 5, May 2013, pp. 72–81.

[12] Z. Niu, S. Zhou, S. Zhou, X. Zhong, J. Wang, "Energy efficiency and resource optimized hyper-cellular mobile communication system architecture and its technical challenges", *SCIENTIA SINICA Informationis*, vol. 42, no. 10, Oct. 2012, pp. 1191-1203.

[13] X. Xu, G. He, S. Zhang, Y. Chen, and S. Xu, "On functionality separation for green mobile networks: Concept study over LTE," *IEEE Commun. Mag.*, vol. 52, no. 5, May 2013, pp. 82–90.

[14] N. Golrezaei, K. Shanmugam, A. G. Dimakis, A. F. Molisch, and Caire, "FemtoCaching: Wireless video content delivery through distributed caching helpers," in *Proc. IEEE INFOCOM*, pp. 1107–1115, Apr. 2012.

[15] N. Bhushan, J. Li, D. Malladi, et al. "Network densification: The dominant theme for wireless evolution into 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, Feb. 2014, pp. 82–89.

**Gang Wu** [M](wugang99@uestc.edu.cn) received his Ph.D. degree from University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2004. He has been an Associate Professor of National Key Laboratory of Science and Technology on Communications, UESTC since 2005. His research interest includes multicarrier waveform and energy-efficient resource allocation for 5G wireless systems. He won IEEE Globecom 2012 Best Paper Award.

**Chenyang Yang** [SM](cyyang@buaa.edu.cn) received her Ph.D. degrees in Electrical Engineering from Beihang University (formerly Beijing University of Aeronautics and Astronautics), Beijing, China, in 1997. She has been a full professor with the School of Electronics and Information Engineering, Beihang University since 1999. Dr. Yang has published over 200 journal and conference papers and filed over 50 patents. She was supported by the 1st Teaching and Research Award Program for Outstanding Young Teachers of Higher Education Institutions by Ministry of Education during 1999-2004. Dr. Yang was the chair of the IEEE Communications Society Beijing chapter during 2008-2012, and the MDC chair of APB of IEEE Communications Society during 2011-2013. Her recent research interests include green radio and interference control for 5G wireless systems.

**Shaoqian Li** [SM] (lsq@uestc.edu.cn)received his M.S.E. degree from the University of Electronic Science and Technology of China in 1984. He is now a professor with UESTC, Director of the National Key Laboratory of Science on Communications, and Dean of the School of Communications and Information Engineering of UESTC. His research interest includes anti-jamming techniques for wireless communications, frequency-hopping techniques, cognitive radio, and spectrum sharing technologies. He has co-authored two books, and published more than 200 refereed journal papers and conference papers, and filed over 50 patents.

**Geoffrey Ye Li** [F'06] (liye@ece.gatech.edu) is a Professor with the School of Electrical and Computer Engineering at Georgia Institute of Technology. His general research interests include wireless communications and statistical signal processing. In these areas, he has published over 300 referred journal and conference papers in addition to 25 granted patents. His publications have been cited over 20,000 times and he is listed as a highly cited researcher by Thomson Reuters. He has been an IEEE Fellow since 2006. He received the *Stephen O. Rice Prize Paper Award* in 2010 and the *WTC Wireless Recognition Award* in 2013 from the IEEE Communications Society and the *James Evans Avant Garde Award* in 2013 and the *Jack Neubauer Memorial Award* in 2014 from the IEEE Vehicular Technology Society.

TABLE I: EE Related Research in Wireless Communications

| Research Areas | Motivations | Research Focus and Application Scenarios |
|---|---|---|
| Information theory | Minimize energy per bit | Minimize transmit power in low SE region, transmit power constraint 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 |

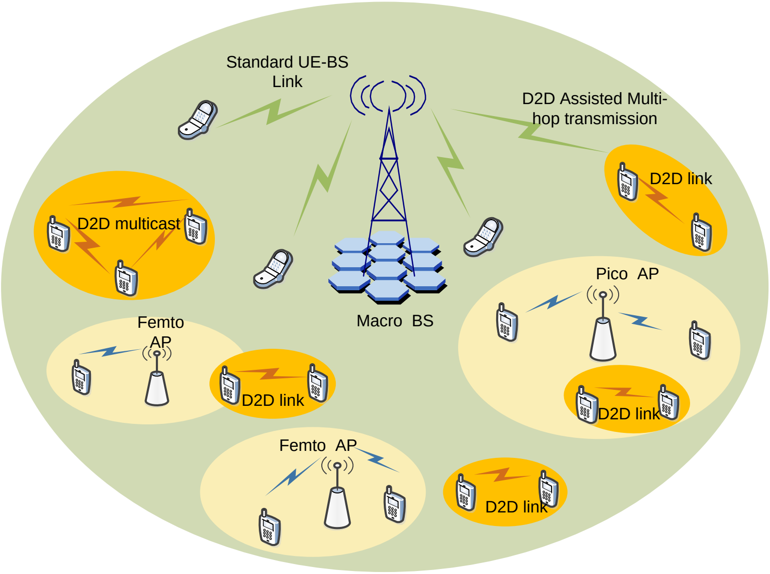

Fig. 1: D2D communications in HetNets

All in-text references underlined in blue are linked to publications on ResearchGate, letting you access and read them immediately.