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Energy Efficiency of Small Cell Networks: Metrics, Methods and Market

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ABSTRACT Although the promising 5G cell network technology has increased the transmitting rate greatly, it has also brought some challenges. The energy efficiency has become an important topic in 5G networks. In this paper, the energy efficiency of small cell networks is analyzed, and the existing objective functions are classified in order to minimize the energy consumption, and to maximize the energy efficiency, harvested energy, and energy-aware transmission. Commonly used metrics were analyzed on equipment, base station, and network levels, respectively. Moreover, the methods for energy efficiency improvement were introduced according to above-mentioned metrics. Afterward, the relationships between energy efficiency, spectrum efficiency, and space efficiency were discussed. In order to improve efficiency on equipment, base station, and network levels, the energy and spectrum market is proposed and guidelines for the future research on metrics, methods, and market are presented. The proposed market was verified by simulations, and the simulation results have shown that the proposed market improves the energy efficiencies effectively.

INDEX TERMS Energy efficiency (EE), small cell networks (SCNs), metrics, energy harvesting (EH), market of energy and spectrum.

I. INTRODUCTION

In the past decades, the mobile communications have experienced an explosive growth. The smart phones have increased demands on mobile media and applications. Therefore, in order to provide a proper communication in the presence of dense traffic, 5G mobile communication technology needs to enhance the present mobile capacity for about thousand times. However, many new techniques intended for 5G have been proposed. One of the most important features of 5G generation mobile communication technology is the hype-dense small cell network (SCN), which has been regarded as a promising solution that can meet current traffic demands.

The SCNs are positioned at offices, homes and high-traffic areas, thus users are always close to the base stations and a high-speed transmission can be achieved at a lower cost. In order to improve the spectrum efficiency, SCNs reuse the spatial spectrum resource using the hype-dense deployment. However, such deployment causes other problems, such as energy efficiency problem. Nowadays, the energy consumption in mobile communications increases rapidly, because the mobile communications represent a great part of people social interaction. Thus, energy efficiency has become interesting and important topic from both economic and environmental reasons. Consequently, the energy efficiency of small cell networks has drawn attention. Many studies on SCN energy efficiency have been obtained. In [1] energy efficiency in the multiple input multiple output (MIMO) systems with orthogonal frequency division multiplexing was studied. Moreover, the sleep mode of small base stations (SBSs) based on dynamic traffic pattern was analyzed in [2]. The energy harvesting technology was employed in [3] and [4] in order to reduce the traditional energy consumption in SCNs. In addition, the cell zooming technology, which dynamically adjusts the coverage of base station according to traffic demands in order to save the energy was presented in [5]. In [6] the focus was on the traffic offloading based on traffic heterogeneity.

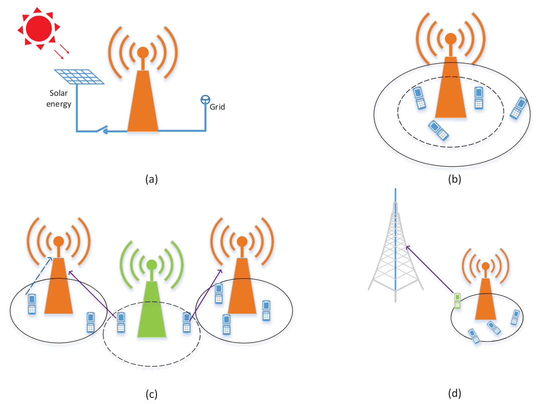

FIGURE 1. Some existing techniques about energy efficiency in small cell networks. a) Energy hybrid access. (b) Cell zooming. (c) Sleep mode. (d) Load balancing.

The content-aware influence on popular content transmission in terms of users' relationships in social networks was investigated in [7]. Some other parameters, such as interference mitigation, beam forming, dynamic spectrum management and component performance were also contributed to improve the SCN energy efficiency [8]–[10]. Four commonly used techniques for energy efficiency enhancement on the base station level are presented in Fig. 1.

Nonetheless, the energy efficiency (EE) can be discussed from different aspects. In [11], the dynamic resource provisioning for EE improvement in wireless access networks was discussed in terms of taxonomy, system models and algorithms. Moreover, the sleep mode was discussed in details in [12] in regards of problem formulation, system model, applications and future research. In mentioned studies, energy efficiency was discussed according to technology levels, applied algorithms and system situations. However, some studies are related to metrics and focused on the specific formulations and unites, instead on functions abstraction into more general metrics. In addition, the relationships between energy, spectrum and space are rarely mentioned and investigated.

To summarize, the main contributions of this paper are as follows: The energy efficiency in small cell networks from the view of different metrics are talked about. The mathematic utility functions of the research related to energy efficiency is investigated and different metrics are generalized into four main categories from different aspects in energy efficiency. The technique level and classical methods are also discussed in the view of metrics. The relationship between energy efficiency, spectrum efficiency and space efficiency is discussed. A energy and spectrum market is proposed to improve all the efficiencies simultaneously. Simulation shows that the proposed market improves the efficiencies effectively.

II. ENERGY EFFICIENCY METRICS

A. ENERGY EFFICIENCY OF SMALL CELL NETWORKS

The energy efficiency has been studied before the SCNs have been proposed as a 5G promising technology, and the traditional definition of energy efficiency is presented by:

$$EE_{trandition} = \frac{\text{Spectrum Benefit}}{\text{Energy Consumption}}, \tag{1}$$

where *Spectrum Benefit* relates to the service quality metric, such as throughput, wherein the focus is on the performance of single equipment or one base station, and *Energy Consumption* denotes the real energy consumption. Compared to the traditional networks, the hyper-dense 5G cell networks have different space dimension factor, which contributes to the energy efficiency metrics. Therefore, on network level the energy efficiency is defined by:

$$EE_{SCN} = \frac{\text{Area Spectrum Benefit}}{\text{Area Energy Consumption}}, \tag{2}$$

where the metric unit is always $bit/s/Hz/J/m^2$, including the spatial influence. In (2), both traditional and space spectrum are considered.

Recently, the small cells deployment, the base station coverage and other related topics have been studied. Although, (2) defines energy efficiency directly, better performances are difficult to achieve, especially in the case of complicated constraints or distributed systems. Therefore, many researchers use some indirect definitions instead of (2) to describe the energy efficiency. According to related works on SCNs energy problem, there are four aspects for energy efficiency improvement: direct improvement of energy efficiency, energy consumption reduction, energy-aware transmission, and obtaining of cheaper and green energy. Many technologies intended for energy efficiency improvement considered just one aspect for efficiency improvement, and only few works considered complicated situations. In the literature, the mathematic metrics have been used for energy efficiency modeling in different situations. However, we have classified them into four main categories, wherein each of categories matches one aspect of energy efficiency, in Table 1.

B. METRICS ON SYSTEM LEVELS

Based on system architecture, the energy efficiency can be considered according to three levels: equipment level, base station level and network level. In this subsection, four previously-mentioned metrics are discussed according to these levels.

1) DIRECT IMPROVEMENT OF ENERGY EFFICIENCY

The most common mathematic metric for energy efficiency (EE) is the ratio between utilities and energy consumption. This ratio represents the most straightforward method for efficiency improvement, wherein the utility represents any important parameter in communications, such as flow, outage probability, and number of base stations, regardless the service quality and experience quality. For instance, when the power is considered on equipment level, the ratio between output power and input power is related to energy consumption. Researchers pay a lot of attention on base station level and network level in SCNs. The cooperation among BSs is

TABLE 1. Energy efficiency metrics.

Metrics	Descriptions	Problems level		Methods	Mathematic tools
		Level	Literature		
$\max \frac{\text{Utility}}{\text{Energy cost}}$	Improve the energy efficiency	Equipment	[8]	Sleep mode, Load balancing, MIMO.	Poisson point process Optimization.
		Base station	[1]		
		Network	[10]		
$\max$ Harvested energy	Gain cheaper and green energy	Equipment	[3]	Energy harvesting, Energy trading	Poisson point process Markove process decision Game theory.
		Base station	[4]		
$\max$ Utility - Energy cost	Reduce the energy consumption	Equipment	[6]	Sleep mode, Load balancing	Dynamic spectrum management, Optimization.
		Base station	[2]		
		Network	[9]		
$\max$ Utility $s.t.$Energy consumption	Transmission based on the energy constraints	Equipment	[15]	MIMO, Load balancing	Poisson point process Optimization.
		Base station	[14]		
		Network	[13]		

very common, while the weighted EE of networks is more popular on network level. In addition, the ratio of spatial spectrum efficiency and spatial energy consumption is used to consider the area communication performance.

2) CHEAPER AND GREENER ENERGY

Two main reasons for energy efficiency consideration refer to economic and environmental factors. Therefore, if the energy is cheaper and greener, the benefits in terms of mentioned aspects would be achieved. Due to development of the green energy technology and low power consumption of SBSs, the cheaper and greener energy in SCNs can be achieved. The related technology mostly refers to base station level and equipment level. From the base station level, the metric is always considered as an energy required to evaluate the energy harvesting performance. Sometimes, the harvested energy is not enough, thus the base station needs to use electric energy from the grid. Then, the weighted sum of energy from different sources is denoted as a metric. The energy is obtaining from multiple sources based on dynamic electric price. However, the energy gaining methods, such as successful harvesting and channel strategy selection, are considered more often on equipment level than on base station level.

3) REDUCTION OF ENERGY CONSUMPTION

Reduction of energy consumption might be considered as an energy gaining method. If the utility is ignored in the metrics, reduction of energy consumption minimizes only the cost. In that situation, the similarity of objective functions is small and their differences represent constraints. Although, the equipment level is focused on the service quality, the network level considers the experience quality. Hence, when different functions are considered, the metric represents the tradeoff between energy cost and other utilities. On equipment level, the tradeoff between flow, sensing, and delay should be made in order to evaluate the basic communication performance. On base station level, utilities might refer to users' experience quality, and on network level, a more general high-level consideration is required, such as economic balancing of traffic demands, energy consumption and deployment cost.

4) ENERGY-AWARE TRANSMISSION

In contrast to the above metrics, here, energy represents a constraint instead of an objective function. However, it still has a positive character in problems solving. Besides the traditional power consumption constraint, in energy-aware transmission, there are other constraint on base station and network levels, such as economic cost of deployment. On equipment level, there are more choices, such as battery harvesting in radio frequency energy, and energy-information tradeoff during transmission in wireless power system. Besides the one-level energy efficiency, some works considered the cross level energy efficiency. For instance, in [13] the load balancing and EE of the macro BS and SBSs were studied.

III. METHODS FOR ENERGY EFFICIENCY IMPROVEMENT

In this section, specific techniques for energy efficiency improvement in small cell networks are discussed according to metrics. We were mainly focused on four techniques intended for base station level in SCNs.

A. SLEEP MODE

Due to people activities, the mobile communication traffic is dynamic both in time and space. Namely, the base stations have a huge traffic load in a certain period of time, but then, the traffic disappears and BSs go to idle state. For instance, the BSs in hot-areas are busy in daytime and idle at night. Moreover, the traffic is also influenced by workdays and weekends. Therefore, base stations should reduce the transmitting power in order to save the energy when the load is light, and work with a full power in huge-traffic periods. The majority of related works are focused on base station level and just some of them are related to the entire network.

- Energy consumption minimization. On base station level, the problem is the tradeoff between service quality and energy cost. The more power, the better service, but the higher cost. On network level, the problems is related to the base station development. The strategy to use a small number of BSs in the case of dynamic traffic in order to provide a better service has drawn the operators' attention.

- Energy efficiency maximization. On network level, the metric is the ratio between area spectrum efficiency and energy efficiency. On base station level, the utility varies from flow to function satisfaction, and from service quality to experience.

B. ENERGY HARVESTING

Nowadays, energy harvesting represents an emerging technology, wherein the main idea is to enable devices to use other energy sources in order to provide the communication. Due to low power consumption in SBSs, the energy harvesting technology provides suitable method for small cell networks. Based on the energy source, the EH technologies can be divided into two categories, low power EH, represented by a radio frequency energy harvesting, which is performed on equipment level, and, solar or wind EH, which is suitable for base station level. For both EH technologies, the majority of metrics are related to maximization of energy gaining and energy-aware transmission.

- Maximization of energy harvesting. Due to difference in sources, the emphasis points of two levels are also different. Namely, the equipment level focuses on the harvesting process details. In addition, the spectrum dynamic selection and sensing are the key methods to pursue more energy in radio frequency EH. On the other hand, on base station level, the most important is matching of energy source model and traffic pattern.
- Energy-aware transmission. On equipment level, for energy saving the most important is the tradeoff between transition and harvesting, then follows the mitigation of contention contributes. On the other hand, on base station level, the dynamics in energy and traffic model are considered. In addition, the topics related to energy store model and traffic prediction for intra-cell and load balancing with EH inter-cell are the most popular.

C. LOAD BALANCING

Similar to the sleep mode, the load balancing is also related to the traffic. The difference is that sleep mode focuses on energy saving and load balancing is focused on traffic service. However, the traffic is not uniformly distributed. Some of the base stations might have heavy load, but nearby BSs might be in the idle state. Therefore, the first base stations may transfer some traffic to second ones in order to obtain a full use of resources and to provide better service to users. The load balancing is performed mainly on base station level and its metric is energy-aware transmission. When the goal is spectrum efficiency improvement, the power limitation always represents the constraint. In some cases, the energy is related to the signal to noise ratio (SNR). Furthermore, the energy efficiency is also related to the total energy consumption in all base stations that offload the traffic, including MBS and SBSs.

D. BS CACHE

The media traffic represents a large part of total mobile traffic. The popular contents, such as social news and popular entertainment, always attract more attention. However, in traditional systems, BSs download the same content on demand from different users, which represents a serious wasting of energy and spectrum. Therefore, the base station should store the popular content in the cache when it is downloaded for the first time. The cache is mainly used on base station level in order to minimize the energy consumption. Nevertheless, the content storing in the cached determines the benefit and efficiency.

There are other technologies used in energy efficiency systems. For example, massive MIMO, another significant feature of the 5G, also improves the energy efficiency at the same time with spectrum efficiency. Simultaneous wireless information and power transmission can provide information and energy for users. Device-to-Device technology allows users to build the communication link and save the power consumption through shortening the distance between BSs and users.

IV. THE MARKET OF SPECTRUM, ENERGY, AND SPATIAL EFFICIENCY

A. TRADEOFF BETWEEN ENERGY EFFICIENCY, SPECTRUM EFFICIENCY AND SPATIAL EFFICIENCY

Due to the SCNs hyper-density, the spatial efficiency becomes more and more important. The spatial factor is involved in energy efficiency metrics, especially on network level. As the first energy efficiency improvement metrics, the area spectrum efficiency and area energy cost, were considered for traditional EE in space domain. However, the deployment problem directly affects the traffic spatial model, and the cell zooming also contributes to the spatial spectrum efficiency.

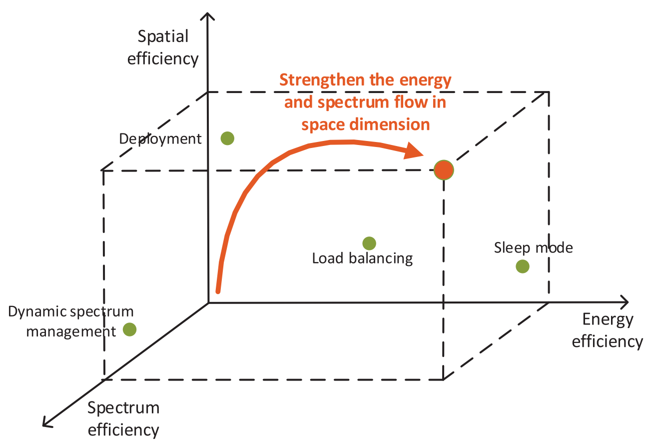

FIGURE 2. The techniques for improvement of energy efficiency, spectrum efficiency and spatial efficiency.

The techniques intended for energy, spectrum, and spatial efficiency improvement are presented in Fig. 2. Some of presented techniques focus just on one or two aspects, without consideration of all aspects. For instance, the dynamic spectrum management and interference mitigation provide an achievement of a high spectrum efficiency. On the other hand, the sleep mode and energy harvesting contribute to energy efficiency improvement. In addition, the deployment refers on the spatial aspect. The load balancing improves the spectrum utilization and energy efficiency through user association. Unfortunately, when one efficiency dimension is increased, the other dimensions are decreased. Therefore, the tradeoff can be consider as a teeter, wherein all techniques and methods put one side up and other side down. Hence, it seems impossible to achieve the win-win situation using the traditional techniques, which motivates us to "change" the teeter in order to achieve high efficiency.

B. THE SPECTRUM AND ENERGY MARKET

There are two ways to "change" the teeter, to bend the board and to rise the supporting point. Bending of the board means to design another tradeoff mechanism that evaluates the efficiency in a new way. For instance, in the cross level situation, more aspects can be combined, such as base station deployment and energy harvesting. The second way, i.e. rising of the supporting point, means to find a new architecture that involves all three dimensions together. The best solution is developing of the market of spectrum, energy and other resource, which allows base stations to trade in order to satisfy the current user needs. The energy and spectrum resources can be transformed into each other by economic behavior at the market. The market provides the spatial efficiency through supply and request balancing.

The spectrum market has been introduced a few years ago, when the licensed sharing access was proposed to solve the disorder in cognitive radio networks. The spectrum resource can be converted into commodity, and the market mechanism plays a role of the market. BSs with spectrum shortage can buy resources, and BSs with light traffic can sell spectrum. Thus, the spectrum can flow between the BSs in the space dimension.

The energy market is similar to the spectrum market. The base stations can sell the harvested energy to the grid when the traffic is light. In addition, BSs can buy the energy from the grid when they need additional energy. The performed action, selling or buying of energy, is totally determined by energy state and traffic load. The market forwards the harvested energy to the grid, which represents the best use of energy and improves overall energy efficiency.

In the following, two markets are combined, and spectrum and energy are considered together. The energy and spectrum resources can flow through the network with dynamic price. At the market, each BS represents seller and buyer at the same time, and its role switches according to its own state and social market price. Basically, there are three ways to create benefit at the market: to sell the energy, to sell the spectrum, and to service more users. The decision process is performed on base station level, while the energy and spectrum flow on network level, Fig. 3. In the left side of Fig. 3, the base station makes decision based on the state

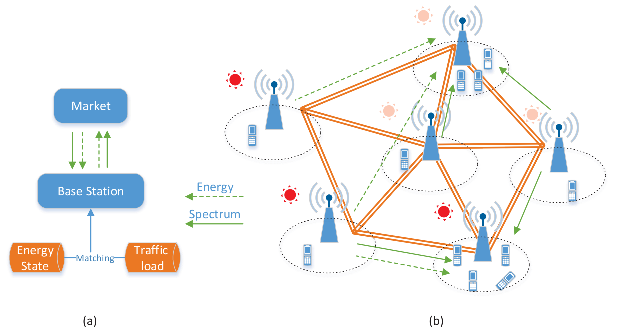

FIGURE 3. The decision process on base station level and flow on network level of the market. (a) The decision in base station level. (b) The flow of energy and spectrum in network level.

of energy buffer and traffic load. If the energy and spectrum resources can satisfy the traffic, the BS may choose one of three following strategies: serve more users to make full use of its resources, sell the redundant energy to the grid, or lend the spectrum to the nearby BSs. Otherwise, it would buy the resources to satisfy the traffic or offload the traffic to nearby users. The decision is not only based on BS state, but it also depends on the price determined by the market. The right subfigure in Fig. 3, represents an example of energy and spectrum market. The BS with the heaviest traffic has the higher harvested energy but it still cannot satisfy the traffic needs. Therefore, BS needs to buy energy from the grid and spectrum from nearby BSs. In the case of strong energy source with a light load, redundant resources are forwarded to the market. Compared to the spectrum, which is limited on the local area, the energy can flow through the grid over the entire network. Therefore, the combined market improves both energy efficiency and spectrum efficiency. Furthermore, considering the market spatial efficiency, it can be concluded that market improves spectrum, energy, and spatial efficiency, simultaneously.

In order to validate the proposed market, the energy cost, the spectrum utilization and the percent of served traffic for three following situations: no market (NM), only local spectrum market (SM), and both spectrum and energy market (SEM), were simulated. The normalized range of energy and spectrum supply, and traffic load were in the range 1-10, 1-8 and 1-12, respectively. The number of base stations was changed from 5 to 18. In the simulations, the energy supply was changed from 4 to 31. Simulation results are presented in Fig. 4 and Fig. 5. As it can be seen in Fig. 4, the efficiency is the best for the market with both energy and spectrum, and the worst for no market case. In addition, the efficiency increases with the increase of number of BSs, because in that case the number of neighbors increases, which provides more resources in the network. As it is presented in Fig. 5, when energy increases, the energy efficiency decreases and other two efficiencies increase. The market with energy and spectrum achieves the best performance with the smallest energy supply. The simulation results show that the market that combines energy and spectrum improves the efficiency effectively.

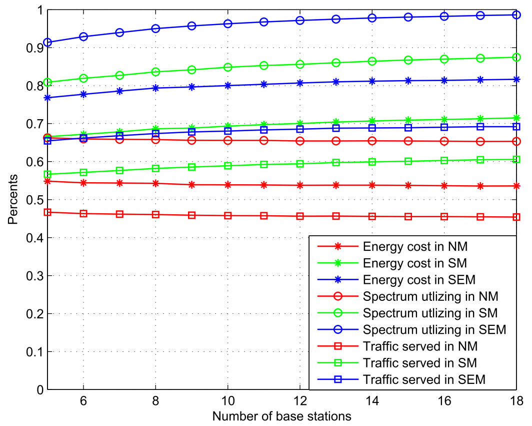

FIGURE 4. The efficiency of: market with both energy and spectrum, market with only spectrum, and no market.

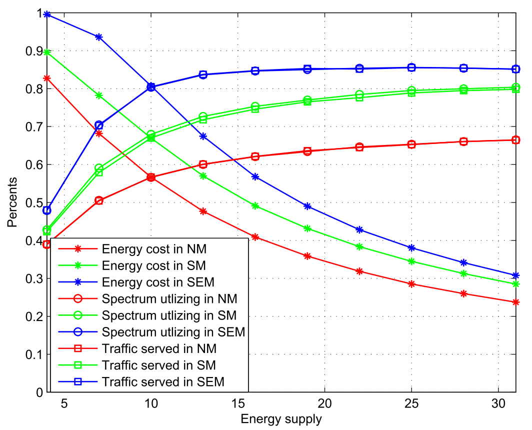

FIGURE 5. The efficiency for different energy supply.

C. FURTHER MARKET IMPROVEMENT

In order to manage and improve the market, certain topics should be further investigated.

1) BREAKING OF BARRIERS IN THE SPATIAL SPECTRUM

In contrast to the energy, the spectrum resource does not need the grid for transmission. This feature brings advantages, but it causes some barriers. The convenience is that the spectrum resource can be easily borrowed and lent between BSs without additional medium. Nonetheless, the range is limited on nearby neighborhood. Thus, the spectrum resources seem to be restricted on local area, they cannot be spread within the entire network. Consequently, the current research hot point is breaking of barriers and promoting of the flow in the spatial spectrum in order to improve the efficiency.

2) DESIGNING OF RULES IN ECONOMIC BEHAVIOR

Selling and buying of resource at the market represent economic behaviors. As already mentioned, the goal of the base stations is to maximize its profit and benefit. The base station determines resource price based on both station current state and future state of total network. The traffic and energy distributions in the space also need to be modeled. Modeling of interaction between multiple players with economic behavior, as well as designing of an incentive mechanism in order to stimulate resources exchange between BSs, represents interesting and challenging topics.

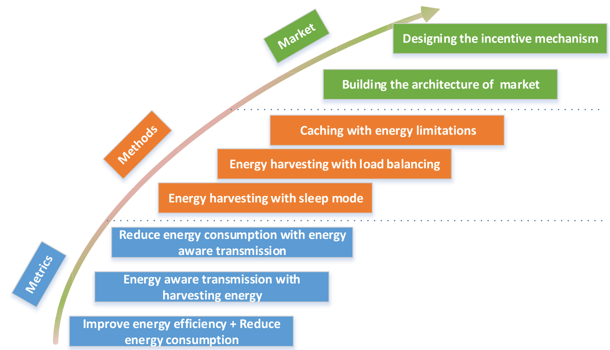

FIGURE 6. Stairs to approaching efficiency in future SCNs.

V. FUTURE RESEARCH ISSUES AND CHALLENGES

Based on discussion presented in this paper, our future work on metrics, methods and market can be summarized as follows, in Fig. 6:

- Combine two or more metrics into one problem. For instance, combining of maximization of energy efficiency and harvested energy, and minimization of energy consumption, based on energy-aware transmission. The load balancing problem considers energy harvesting as an energy source. Moreover, the non-uniform and dynamic traffics can be joined, using the load balancing match of energy with load, in order to achieve higher energy efficiency.
- Design the new tradeoff between three mentioned efficiencies. Moreover, crossing of the technique levels, and consideration of weighted energy efficiency of macro and micro base stations should be performed. In addition, according to the structure of the small cell networks, we should model the leader and follow relationship between the MBS, SBSs and users through the Stackelberg game.
- Furthermore, the following should be done: focusing on the incentive mechanism and market rules, studying of economic behavior at energy and spectrum market, designing of a proper incentive mechanism that can stimulate energy and spectrum exchange between base stations, and lastly, breaking of barriers in the spatial spectrum field.

However, the present challenges are as follows:

- Accurate modeling of energy harvesting. Namely, energy harvesting represents the base of the proposed market, but the existing model is fuzzy because of complicated environment. Therefore, a more accurate energy harvesting model would provide better trade of both energy and spectrum.
- Combining the communication with economic behavior. The market is totally economical, but the situations are physical. The main goal is to provide the mechanism that uses the economic rules and behaviors for modeling

of communications process without losing of the original physical meaning.

VI. CONCLUSION

In this paper, the energy efficiency of small cell networks is analyzed and discussed. The brief review of the related works was obtained and the objective functions were classified according to four metrics: maximization of energy efficiency, minimization of energy consumption, maximization of harvested energy, and maximization of energy-aware transmission. After analysis of metrics in terms of system levels, the load balancing, the sleep mode, the energy harvesting and the cache technologies were introduced. A market that combines energy and spectrum was proposed in order to improve the energy, spectrum and spatial efficiencies simultaneously. The proposed market was verified by simulations. The simulation results have shown that proposed market improves the efficiencies effectively. Lastly, the guidelines for future research on further energy efficiency improvement were presented.

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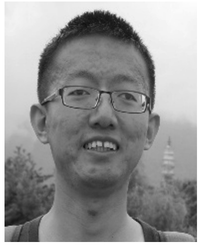

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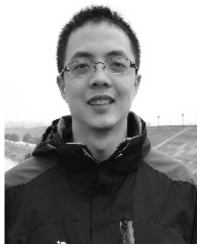

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