ON GREENING CELLULAR NETWORKS VIA MULTICELL COOPERATION

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ABSTRACT

Recently, green communications has received much attention. Cellular networks are among the major energy hoggers of communication networks, and their contributions to the global energy consumption increase fast. Therefore, greening cellular networks is crucial to reducing the carbon footprint of information and communications technology. In this article, we overview the multicell cooperation solutions for improving the energy efficiency of cellular networks. First, we introduce traffic-intensity-aware multicell cooperation, which adapts the network layout of cellular networks according to user traffic demands in order to reduce the number of active base stations. Then we discuss energy-aware multicell cooperation, which offloads traffic from on-grid base stations to off-grid base stations powered by renewable energy, thereby reducing the on-grid power consumption. In addition, we investigate improving the energy efficiency of cellular networks by exploiting coordinated multipoint transmissions. Finally, we discuss the characteristics of future cellular networks, and the challenges in achieving energy-efficient multicell cooperation in future cellular networks.

INTRODUCTION

Greening is not merely a trendy concept, but is becoming a necessity to bolster social, environmental, and economic sustainability. Naturally, green communications has received much attention recently. As cellular network infrastructures and mobile devices proliferate, an increasing number of users rely on cellular networks in their daily lives. As a result, the energy consumption of cellular networks keeps increasing. Therefore, greening cellular networks is attracting tremendous research efforts in both academia and industry [1]. Meanwhile, it has been shown that, with the aid of multicell cooperation, the performance of a cellular network in terms of throughput and coverage can be enhanced significantly. However, the potential of multicell cooperation on improving the energy efficiency of cellular networks remains to be unlocked. This article overviews the multicell cooperation solutions for improving the energy efficiency of cellular networks.

The energy consumption of a cellular network is mainly drawn from base stations (BSs), which account for more than 50 percent of the energy consumption of the network. Thus, improving the energy efficiency of BSs is crucial to green cellular networks. Taking advantage of multicell cooperation, the energy efficiency of cellular networks can be improved from three aspects. The first one is to reduce the number of active BSs required to serve users in an area [2]. The solutions are to adapt the network layout according to traffic demands. The idea is to switch off BSs when their traffic loads are below a certain threshold for a certain period of time. When some BSs are switched off, radio coverage and service provisioning are taken care of by their neighboring cells. The second aspect is to associate users with green BSs powered by renewable energy. Through multicell cooperation, off-grid BSs enlarge their service area while on-grid BSs shrink their service area. Zhou *et al.* [3] proposed the handover parameter tuning algorithm and power control algorithm to guide mobile users to associate with BSs powered by renewable energy, thus reducing on-grid power expenses. Han and Ansari [4] proposed an energy-aware cell size adaptation algorithm named ICE. This algorithm balances the energy consumption among BSs, enables more users to be served with green energy, and therefore reduces the on-grid energy consumption. Envisioning future BSs to be powered by multiple types of energy sources (e.g., the grid, solar energy, and wind energy), Han and Ansari [5] proposed to optimize the utilization of green energy for cellular networks by cell size optimization. The proposed algorithm achieves significant main grid energy savings by scheduling the green energy consumption along the time domain for individual BSs, and balancing the green energy consumption among BSs for the cellular network.

The third aspect is to exploit coordinated multipoint (CoMP) transmissions to improve the energy efficiency of cellular networks [6]. On one hand, with the aid of multicell cooperation, the energy efficiency of BSs on serving cell edge users is increased. On the other hand, the coverage area of BSs can be expanded by adopting multicell cooperation, thus further reducing the number of active BSs required to cover a certain area. In addition to discussing the multicell

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[1] The static power consumption of a BS refers to the power consumption of the BS when there are no active users in the coverage of the BS.

cooperation solutions, we investigate the challenges for multicell cooperation in future cellular networks.

TRAFFIC INTENSITY AWARE MULTICELL COOPERATION

There are two reasons traffic demands of cellular networks experience fluctuations. The first one is the typical day-night behavior of users. Mobile users are usually more active in terms of cell phone usage during the day than during the night, and therefore, traffic demands during the day are higher than those at night. The second reason is the mobility of users. Users tend to move to their office districts during working hours and come back to their residential areas after work. This results in the need for large capacity in both areas at peak usage hours, but reduced requirements during off-peak hours. However, cellular networks are usually dimensioned for peak hour traffic, and thus, most of the BSs work at low work load during off-peak hours. Due to the high static power consumption,[1] BSs usually experience poor energy efficiency when they are operating under a low work load. In addition, cellular networks are typically optimized for the purpose of providing coverage rather than operating at full load. Therefore, even during peak hours, the utilization of BSs may be inefficient regarding energy usage. Adapting the network layout of cellular networks according to traffic demands has been proposed to improve the energy efficiency of cellular networks. The network layout adaptation is achieved by dynamically switching BSs on/off. Figure 1 shows several scenarios of network layout adaptations. Figure 1a shows the original network layout, in which each BS has three sectors. For the green cell, if most of the traffic demands on it are coming from sector three, and the traffic demands in sectors one and two are lower than a predefined threshold, the green cell could switch off sectors one and two to save energy, and the users in the sectors that are switched off will be served by the neighboring cells. In this case, the network layout after the adaptation is shown in Fig. 1b. If traffic demands from sector three of the green cell also decrease below the threshold, the entire green cell is switched off, and the network layout is adapted, as shown in Fig. 1c. Under this scenario, the radio coverage and service provisioning in the green cell are taken care of by its active neighboring cells. When a BS is switched off, the energy consumed by its radio transceivers, processing circuits, and air conditioners can be saved. Therefore, adapting the network layout of cellular networks according to traffic demands can save a significant amount of energy consumed by cellular networks.

While network layout adaptation can potentially reduce the energy consumption of cellular networks, it must meet two service requirements:

- The minimum coverage requirement
- The minimum quality of service (QoS) requirements of all mobile users

Therefore, in carrying out network layout adaptation, multicell cooperation is needed to guar-

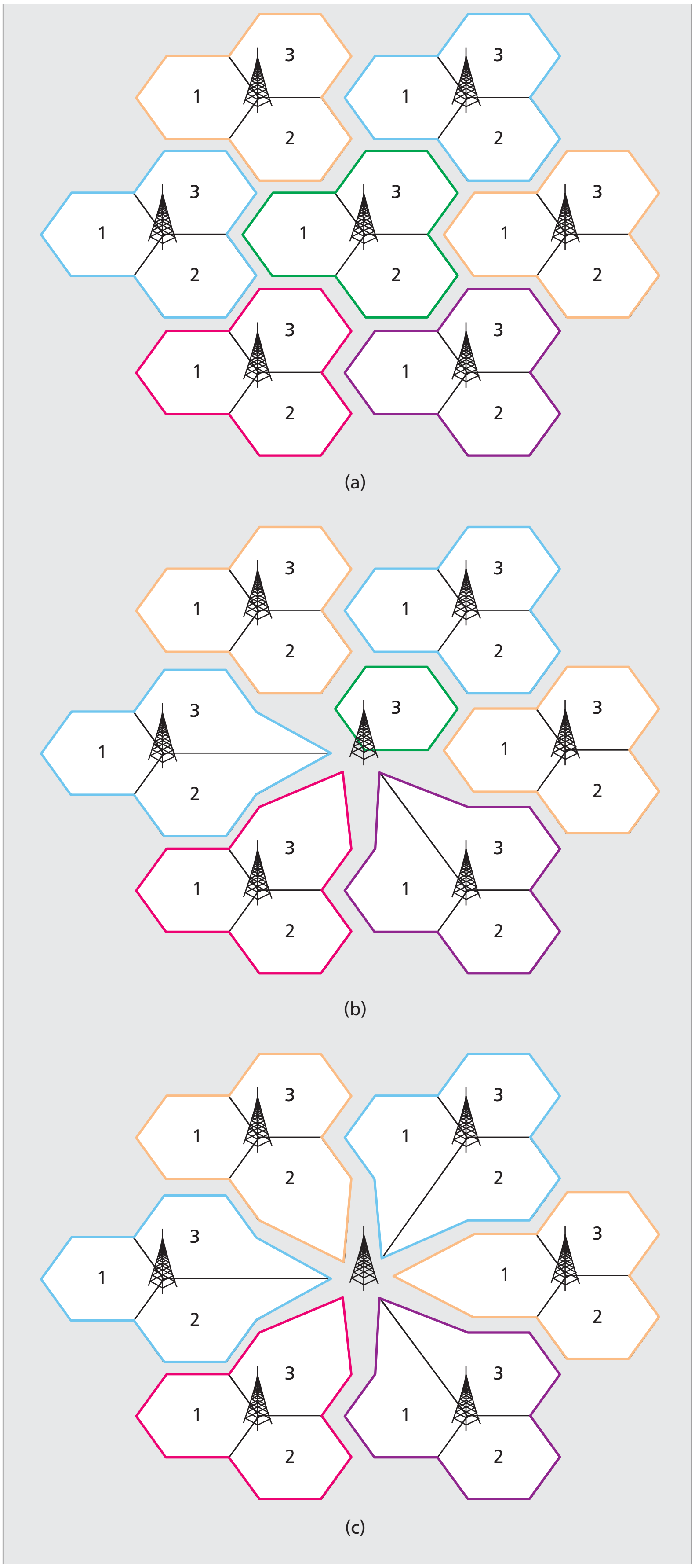

Figure 1. *Illustrations of network layout adaptations for macro cellular sites: a) original network layout; b) BS partially switched off; c) BS entirely switched off.*

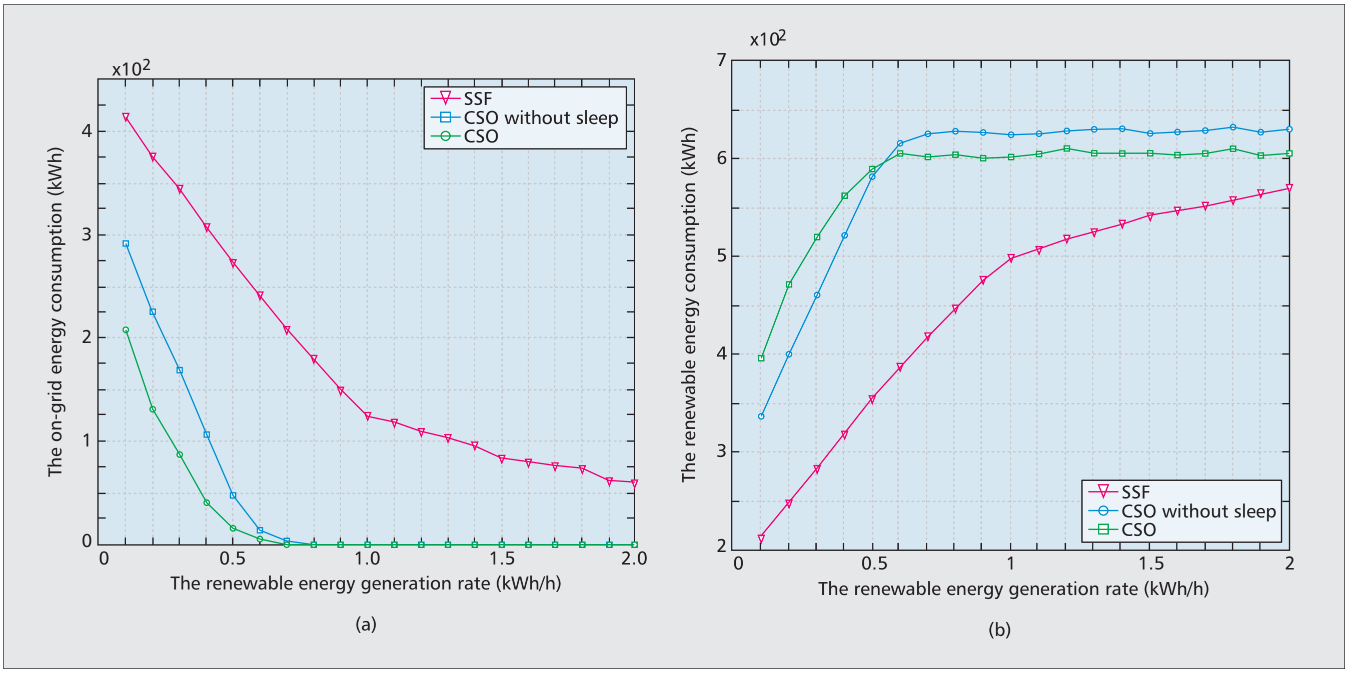

Figure 2. *Energy utilization of the cellular network: a) on-grid energy consumption; b) renewable energy consumption.*

antee service requirements. Otherwise, it will result in a high call blocking probability and severe QoS degradation. For example, two adjacent BSs both experience low traffic demands. However, only one BS can be switched off to save energy, and the other BS should be active to sustain the service provisioning in both coverage areas. In this case, if both BSs are switched off according to their own traffic demands, their subscribers will lose connections. Therefore, cooperation among BSs is essential to enable traffic-intensity-aware network layout adaptation.

COOPERATION TO ESTIMATE TRAFFIC DEMANDS

Network layout adaptation is based on the estimated traffic demands at individual cells. The traffic demand estimation at individual cells requires the cooperation of their neighboring cells. To avoid frequently switching BSs on/off, they are switched off only when their traffic demands are less than a predefined threshold for a minimum period, T. Therefore, the estimated traffic demands should represent the traffic demands at individual cells for at least a time period of length T. Hence, traffic demands at a BS consist of three parts: traffic demands from users who are currently attached to the BS, traffic demands from users who will hand over to other BSs, and traffic demands from users who will hand over to the BS from its neighboring BSs. While the first two components can be measured and estimated by individual BSs, the estimation of the third component requires cooperation from neighboring cells. Two factors contribute to the handover traffic from the neighboring cells. The first one is the user mobility. A user's motion, including the direction and velocity, can be measured by various signal processing methods. Therefore, individual BSs can predict:

- How many users will hand over to other cells in the near future
- To which cells these users are highly likely to hand over

Such information is important for their neighboring BSs to estimate their traffic demands. The second reason for handover traffic is the switching off of neighboring BSs. If one of the neighboring cells is switched off, the users under its coverage will be handed over to its neighboring cells, thus increasing traffic demands of the neighboring cells. Therefore, cooperation among radio cells is important for the traffic demand estimation at individual cells.

COOPERATION TO OPTIMIZE THE SWITCHING OFF STRATEGY

With the traffic demand estimation, cellular networks optimize the switching on/off strategies to maximize the energy saving while guaranteeing users' minimal service requirements. Currently, most existing switching on/off strategies are centralized algorithms, which assume that there is a central controller that collects the operation information of all BSs and optimizes network layout adaptations. Three methods have been proposed to determine which BSs are to be switched off. The first one is randomly switching off BSs with low traffic loads. This method mainly applies to BSs in the night zone, where few users are active. The method randomly switches off some BSs to save energy, and the remaining BSs provide coverage for the area. The second method is a greedy algorithm, which enforces BSs with higher traffic loads to serve more users and switches off BSs with no traffic load. The third method is based on the user–BS distance. The required transmission power of BSs for serving users depends on the distance between users and BSs. The

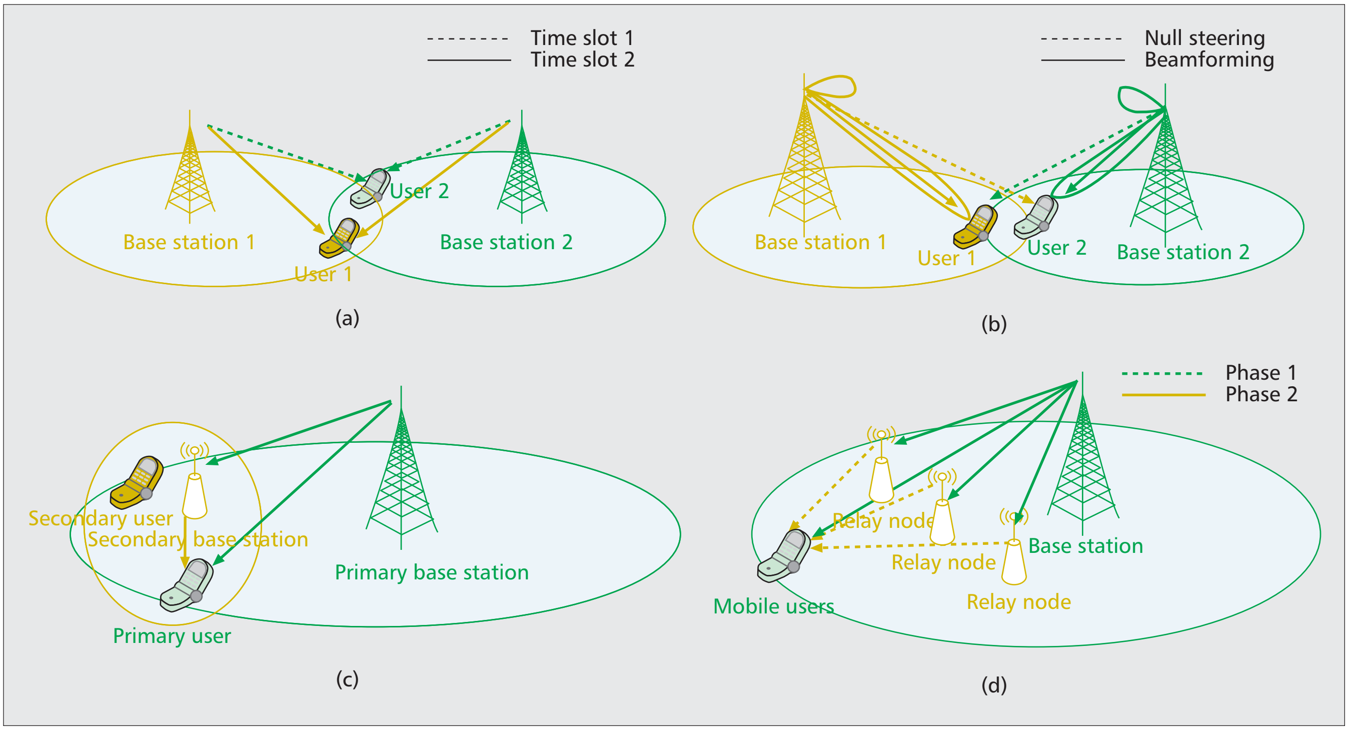

Figure 3. *Energy utilization of the cellular network: a) joint transmission; b) cooperative beamforming; c) cooperative relaying; d) distributed space-time coding.*

longer the distance, the greater the transmission power required in order to meet users' minimal service requirements. Therefore, the user–BS distance can be an indicator of the energy efficiency of cellular networks: the shorter the average user–BS distance, the higher the energy efficiency. Hence, the algorithm tends to switch off BSs with the longest user–BS distance to improve the energy efficiency of cellular networks.

Centralized algorithms, however, require the channel state information and traffic load information of every cell. Collecting this information centrally may impose tremendous communication overheads, and thus reduce the effectiveness of centralized algorithms in improving energy efficiency. Therefore, distributed algorithms are favored, especially for heterogeneous networks that consist of various types of cells such as macrocells, microcells, picocells, and femtocells. To enable distributed algorithms, individual cells may cooperatively form coalitions, and share the channel state information and traffic load information. Based on the shared information, individual BSs optimize their operation strategies to minimize the total energy consumption of the BS coalition.

ENERGY AWARE MULTICELL COOPERATION

With the worldwide penetration of distributed electricity generation at medium and low voltages, it is proved that renewable energy such as sustainable biofuels, and solar and wind energy can be effectively utilized to substantially reduce carbon emission. Therefore, researchers have proposed to power BSs with renewable energy to save the on-grid energy consumption and reduce the carbon footprint. Nokia Siemens Networks [7] has developed off-grid BSs that rely on a combination of solar and wind power supported by fuel cell and deep cycle battery technologies. Compared to on-grid BSs, off-grid BSs achieve zero carbon emission and save a significant amount of on-grid energy. However, due to the dynamic nature of renewable resources, renewable energy generation highly depends on environmental factors such as temperature, light intensity, and wind velocity. In addition, because of the limited battery capacity, generated energy should be utilized well to avoid energy overflow. Therefore, how to optimize the utilization of renewable energy in cellular networks is not a trivial problem. One intuitive solution for this problem is the energy-aware cell breathing method. Here, "energy-aware" pertains to two perspectives. The first one is the awareness of energy sources such that users are guided to draw energy from off-grid BSs rather than on-grid BSs. This can be achieved by enlarging the cell sizes of off-grid BSs and shrinking those of on-grid BSs [3]. The second perspective is the awareness of the amount of energy storage such that off-grid BSs with higher amounts of energy storage are forced to serve a larger area. In this way, energy overflow can be avoided, thus enabling the renewable energy generation system to harvest more energy from renewable sources [4]. The energy-aware cell breathing technique is a step forward to further traffic-intensity-aware network layout adaptations. In addition to the traffic load information and channel state information, energy-aware cell breathing requires multiple cells to cooperatively share the energy informa-

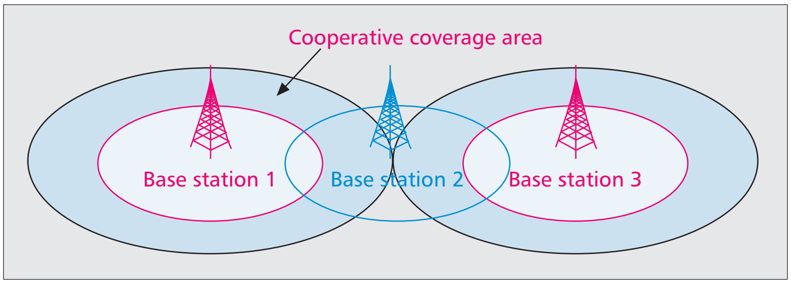

Figure 4. *Cooperation to increase coverage area.*

tion, including the estimated amount of energy arrival and the amount of energy storage, and to coordinate to minimize the energy consumption of cellular networks.

A CASE STUDY

Envisioning future BSs powered by multiple types of energy sources (e.g., on-grid energy and renewable energy), we investigate the optimal energy utilization strategies in cellular networks with both on-grid and off-grid BSs. In such cellular networks, BSs are powered by renewable energy if they have enough renewable energy storage; otherwise, the BSs switch to on-grid energy to serve mobile users. To optimize energy utilization, BSs cooperatively determine their cell size through energy-aware cell breathing based on the proposed cell size optimization (CSO) algorithm [5]. By cooperative cell breathing, the on-grid energy consumption of the cellular network over a period of time consisting of several cell size adaptations is minimized. The optimal energy utilization strategy includes two parts: the multi-stage energy allocation policy and the single-stage energy consumption minimization. The multi-stage energy allocation policy determines the amount of renewable energy allocated at individual off-grid BSs during each cell size update. The single-stage energy consumption minimization involves two steps. The first step is to minimize the number of active on-grid BSs by offloading traffic cell breathing. On-grid BSs shrink their cell sizes to enforce the associated users to hand over to off-grid BSs, and the off-grid BSs with higher amounts of energy storage enlarge their cell sizes to absorb more users. The second step is to minimize the number of active BSs (both on-grid and off-grid) by applying the sleep mode checking algorithm. When traffic demands on individual BSs are lower than a threshold, the BSs seek to put themselves into sleep mode by cooperating with their neighboring cells. If the BS is in sleep mode, its associated users will be handed over to its neighboring cells. In this case, if the neighboring BSs have enough energy storage to serve the handed over users, and the total energy consumption of the cellular network is reduced, the BS is switched into sleep mode to save energy.

Figure 2 shows the comparisons between the CSO algorithm and the strongest-signal first method, which always associates a user with the BS with the strongest received signal strength. Figure 2a shows the on-grid energy consumption at different renewable energy generation rates. In this simulation, there are 400 mobile users in the mobile network. As the renewable energy generation rate increases, the on-grid energy consumption of the mobile network is reduced. When the renewable energy generation rate is larger, more electricity is generated from renewable energy. Therefore, more BSs can serve mobile users using electricity generated by renewable energy instead of consuming on-grid energy. When the renewable energy generation rate is larger than 0.6 kWh/h, the CSO algorithm achieves zero on-grid energy consumption by optimizing the cell size of each BS, while the SSF algorithm still consumes a significant amount of on-grid energy. When the renewable energy generation rate is low, the CSO algorithm saves more than 200 kWh electricity than the SSF algorithm. As the generation rate increases, the gap between the energy consumption of CSO and that of SSF narrows because the CSO algorithm has already achieved zero energy consumption, and the energy consumption of SSF reduces due to increased availability of renewable energy. Figure 2b shows the renewable energy consumption at different energy generation rates. When the energy generation rate is less than 0.7 kWh/h, the renewable energy consumptions of all the simulated algorithms increase as the renewable energy generation rate increases. This is because the larger the renewable energy generation rate, the more renewable energy can be used to serve mobile users. In addition, the CSO algorithm consumes more renewable energy than the SSF algorithm does because the CSO algorithm optimizes the cell sizes of BSs and maximizes the utilization of renewable energy in order to reduce the on-grid energy consumption. When the renewable energy generation rate is larger than 0.7 kWh/h, the renewable energy consumption of the CSO algorithm does not change much, while that of SSF keeps increasing. This is because when the renewable energy generation rate is larger than 0.7 kWh/h, the on-grid energy consumption of the CSO algorithm is zero, as shown in Fig. 2a. This indicates that all the users are served by renewable energy. Therefore, the renewable energy consumption of the CSO algorithm reflects the total energy consumption of the network, which is similar under different energy generation rates in the simulation.

ENERGY EFFICIENT COMP TRANSMISSION

Coordinated multipoint (CoMP) transmission is a key technology for future mobile communication systems. In CoMP transmission, multiple BSs cooperatively transmit data to mobile users to improve their receiving signal quality. BSs share the required information for cooperation via high-speed wired links. Based on the information, BSs determine joint processing and coordinated scheduling strategies. While CoMP transmission has been proved to be effective in improving the data rate and spectral efficiency of cell edge users [8], its potential for improving the energy efficiency of cellular networks has not been fully exploited. In this section, we discuss the potentials of CoMP transmission in greening cellular networks.

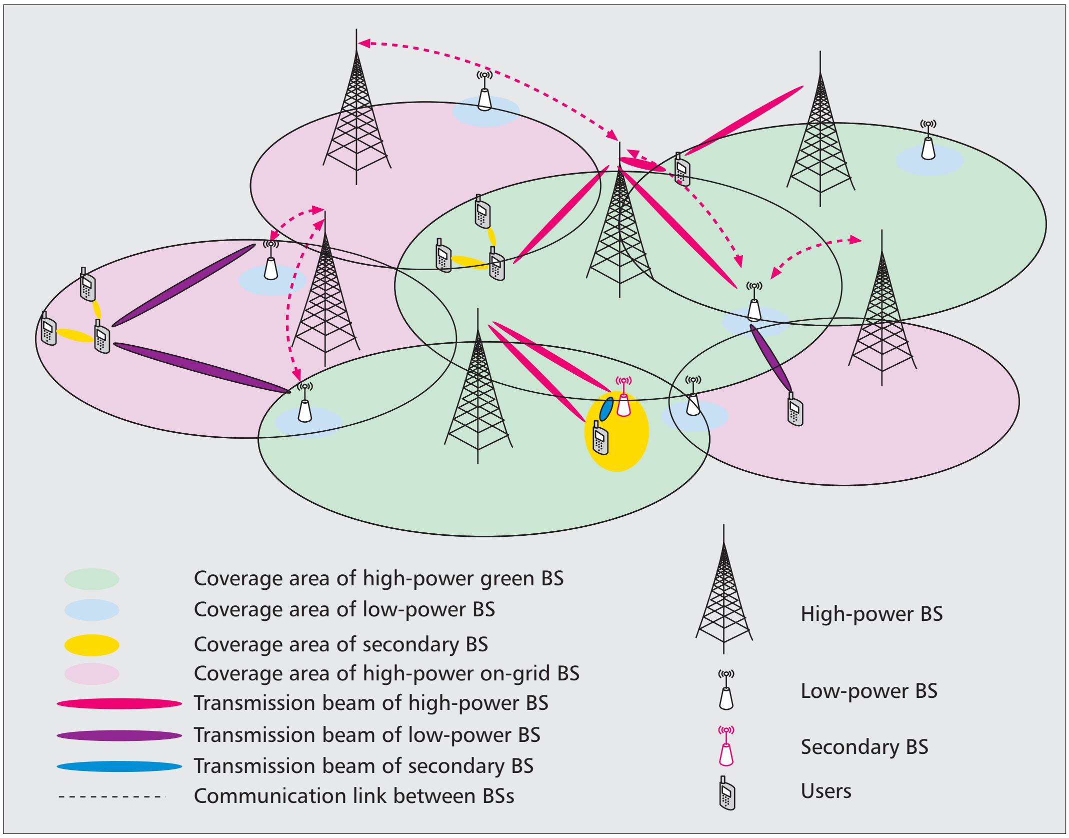

Figure 5. *Future cellular networks with holistic cooperation.*

Owing to joint transmission, cell edge users experience higher receiving signal strength and lower interference, therefore requiring less transmission power from both BSs. Thus, the joint transmission improves energy efficiency of the cell edge communications.

INCREASE ENERGY EFFICIENCY FOR CELL EDGE COMMUNICATIONS

BSs usually have lower energy efficiency in serving the users at the cell edge than in serving the users within the cell. This is not only because cell edge users are far away from BSs and require more transmission power, but also because cell edge users experience more interference from neighboring cells. Multicell cooperation can improve energy efficiency for cell edge communications [6].

Joint Transmission — Joint transmission exploits the cooperation among neighboring BSs to transmit the same information to individual users located at the cell edge [9]. Figure 3a illustrates the joint transmission scheme. User 2 associates with BS 2 while user 1 associates with BS 1. Instead of serving their associated users independently, BSs 1 and 2 cooperatively transmit information to their users. For example, if both BSs apply time-division multiple access (TDMA) in the first time slot, both BS 1 and 2 transmit the same information to user 2. The user combines the signals from both BSs to decode the information. In the second time slot, the BSs cooperatively serve user 1. Due to joint transmission, cell edge users experience higher receiving signal strength and lower interference, hence requiring less transmission power from both BSs. Thus, joint transmission improves the energy efficiency of the cell edge communications.

Cooperative Beamforming — In cooperative beamforming, a BS forms radio beams to enhance the signal strength of its serving users while forming null steering toward users in its neighboring cells. As shown in Fig. 3b, BS 1 forms the radio beam toward its associated user, user 1, to increase the user's receiving signal strength. On the other hand, in order to reduce the interference to user 2 who is served by a neighboring BS, BS 1 forms the null steering toward user 2. BS 2 executes the same operation as BS 1. Therefore, through cooperative beamforming, the signal-to-noise ratio (SNR) of both user 1 and user 2 is enhanced. Thus, less transmission power is required for BSs to serve the cell edge users, and the energy efficiency of cell edge communications is increased.

Cooperative Relaying — Taking advantage of cognitive radio techniques, cooperation can be exploited between a primary cell and a secondary cell as shown in Fig. 3c. The secondary BS cooperatively relays the signal from the primary BS to the primary user. The primary user combines the signals from both the primary and secondary BSs to decode the information. To stimulate cooperative relaying, the primary BS grants the secondary BS some spectrum that can be utilized for communications between the secondary BS and secondary users. By cooperating with secondary BSs, the transmission power required from primary BSs to serve the cell edge users is reduced. Therefore, the cooperative relay scheme reduces the power consumption of primary BSs [10]. However, due to the time-varying

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wireless channels, the scheduling delay involved in the relaying process may increase the outage probability. Fan *et al.* [11] showed that the outage probability caused by the scheduling delay can be alleviated by optimizing the transmission power of the network nodes.

Distributed Space-Time Coding — Distributed space-time coding [12] explores the spatial diversity of both the relay nodes and the mobile users to combat multipath fading, and can be applied to improve the spectral and energy efficiency of cell edge users. As illustrated in Fig. 3d, the distributed space-time coding scheme consists of two phases. In the first phase, the BS broadcasts a data packet to its destination and the potential relays. In the second phase, the potential relays that can decode the data packet cooperatively transmit the decoded data packet to the destination using a suitable space-time code. By exploring spatial diversity, distributed spaced-time coded cooperative transmission improves the diversity gain of cellular networks. However, the multiplexing gain of the wireless system may be sacrificed [13]. Zou *et al.* [13] proposed an opportunistic distributed space-time coding (O-DSTC) scheme to increase the multiplexing gain. Taking advantage of DSTC cooperative transmission, the spectral efficiency is increased. As a result, fewer transmissions are required in order to transmit a given number of data packets. Therefore, the energy efficiency of the cellular networks is enhanced.

ENABLE MORE BSs TO ENTER SLEEP MODE

As discussed in the previous subsection, CoMP transmission (e.g., joint transmission) enhances the receiving SNR of cell edge users, implying that BSs are able to cover a larger area with the same transmission power. Therefore, under low traffic demands, adopting the CoMP transmission can reduce the number of BSs required to cover an area, thus improving the energy efficiency of cellular networks [14].

As presented earlier, traffic-intensity-aware multicell cooperation enables BSs with low traffic demands to go into sleep mode to save energy. The users in the off cells will be served by their active neighboring cells. However, due to the limitation of BSs' maximal transmission power, a few BSs should stay awake to provide coverage in the area. By applying CoMP transmission, the number of required active BSs can be further reduced. As illustrated in Fig. 4, the inner circle of BS 1 is the original coverage area, while the outer circle indicates the coverage area after cooperation with its neighboring BS, BS 3. The green area is the additional coverage area achieved by multicell cooperation. Under the condition of lower traffic demands, if there is no cooperation among BSs, three BSs have to stay awake to cover the whole area. However, if multicell cooperation is enabled, BS 1 and BS 3 can provide services to the users in the area by applying cooperative transmission; thus, BS 2 can be switched into sleep mode. Therefore, the total energy consumption of cellular networks is reduced.

FUTURE CELLULAR NETWORKS WITH MULTICELL COOPERATION

With advances of cellular networks and communication techniques, future cellular networks will be featured as heterogeneous networks in terms of both network deployments and communication techniques, as shown in Fig. 5.

Regarding network deployments, heterogeneous networks refer to deploying a mix of high-power and low-power BSs in order to satisfy the traffic demands of service areas. High-power BSs (e.g., macro and micro BSs) are deployed to provide coverage to a large area, while low-power BSs are deployed to provide high capacity within a small coverage area. In addition, based on energy supplies, BSs can be further divided into two types: on-grid BSs, and off-grid BSs powered by green energy such as solar power and wind power. Therefore, future heterogeneous networks consist of four types of BSs: high-power on-grid BSs, high-power off-grid BSs, low-power on-grid BSs, and low-power off-grid BSs. In terms of technology diversity, heterogeneous networks consist of a variety of technologies such as multiple input multiple output (MIMO), cooperative networking, and cognitive networking. Taking advantage of the increasing network diversity, BSs have more cooperation opportunities, and thus can achieve additional energy savings. However, realizing optimal multicell cooperation is not trivial.

Coalition Formulation — The problem of coalition formation is to determine the coalition size and members of the coalition. Although the problem of coalition formation is well studied in the field of economics, and some game theory methods have been applied to solve the coalition formation problem in wireless networks, few models can be directly applied to form the coalitions of BSs for the purpose of reducing the energy consumption of cellular networks. This is because the original coalition formation problem is to form a coalition to maximize the benefit of all the members in the coalition, while the problem of forming coalitions of BSs is to maximize total benefits of the coalitions. In addition, due to the diversity of BSs and radio access technologies, a successful coalition may consist of BSs and techniques that are complementary to each other to maximize the energy savings of the coalition. Hence, novel models or methods of coalition forming must be developed to facilitate energy-efficient multicell cooperation.

Green Energy Utilization — For the sake of environmental friendliness, off-grid BSs powered by renewable energy are favored over on-grid BSs. In order to optimize the utilization of off-grid BSs, the fundamental design issue is to effectively utilize the harvested energy to sustain traffic demands of users in the network. The optimal utilization of green energy over a period of time depends on the characteristics of the energy arrival and energy consumption at the current stage as well as in future stages, and on the cooperation strategies of the neighboring cells or cooperating cells.

Incentive Mechanism — Note that in future heterogeneous networks, multicell cooperation may involve cells not owned by the same operator. For example, the coalition may consist of a BS from a different operator, a secondary BS operated via cognitive radio, and a relaying cell formed by mobile users. To incentivize cooperation among these cells, a simple but effective incentive mechanism should be exploited.

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CONCLUSION

This article discusses how to reduce the energy consumption of cellular networks via multicell cooperation. We focus on three multicell cooperation scenarios that enhance energy efficiency of cellular networks. The first one is traffic-intensity-aware multicell cooperation, in which multiple cells cooperatively estimate traffic demands and adapt the network layout based on the estimated traffic demands. Through network layout adaptation, the number of active BSs can be reduced, thus reducing the energy consumption of cellular networks. The second scenario is energy-aware multicell cooperation, in which off-grid BSs powered by green energy are enforced to serve a large area to reduce the on-grid power consumption. The third one is energy-efficient CoMP transmission, in which the overall energy consumption is reduced by improving the energy efficiency of BSs in serving cell edge users. In addition, we discuss the diversity of future cellular networks in terms of radio access technologies and BS characteristics, and the challenges to optimally exploit multicell cooperation by capitalizing on diversities.

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BIOGRAPHIES

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NIRWAN ANSARI [S'78, M'83, SM'94, F'09] received his B.S.E.E. (summa cum laude with a perfect GPA) from NJIT, his M.S.E.E. from the University of Michigan, Ann Arbor, and his Ph.D. from Purdue University, West Lafayette, Indiana. He joined NJIT in 1988, where he is a professor of electrical and computer engineering. He has also assumed various administrative positions at NJIT. He has been a visiting (chair/honorary) professor at several universities. His current research focuses on various aspects of broadband networks and multimedia communications. He has served on the Editorial/Advisory Boards of eight journals. He was elected to serve on the IEEE Communications Society (ComSoc) Board of Governors as a member-at-large (2013–2014) as well as IEEE Region 1 Board of Governors as the IEEE North Jersey Section Chair. He has chaired ComSoc technical committees, and has actively organized numerous IEEE international conferences/symposia/workshops, assuming leadership roles as Chair or TPC Chair for various conferences, symposia, and workshops. He has authored *Computational Intelligence for Optimization* (Springer 1997) with E.S.H. Hou and *Media Access Control and Resource Allocation for Next Generation Passive Optical Networks* (Springer, 2013) with J. Zhang, and edited *Neural Networks in Telecommunications* (Springer 1994) with B. Yuhas. He has also contributed over 400 publications, over one third of which were published in widely cited refereed journals/magazines. He has been granted over 15 U.S. patents. He has also guest edited a number of special issues, covering various emerging topics in communications and networking. He has frequently been selected to deliver keynote addresses, distinguished lectures, and tutorials. Some of his recent recognitions include a couple of best paper awards, several Excellence in Teaching Awards, a Thomas Alva Edison Patent Award (2010), an NJ Inventors Hall of Fame Inventor of the Year Award (2012), and designation as a ComSoc Distinguished Lecturer (2006–2009).