SUSTAINABLE COMMUNICATION AND NETWORKING IN TWO-TIER GREEN CELLULAR NETWORKS

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ABSTRACT

With the advances of green energy technologies, clean and sustainable energy sources have been considered as alternative energy sources for powering cellular networks. However, it is very challenging to exploit the charged energy to satisfy the QoS demands of wireless multimedia services due to the dynamics in the energy charging and discharging processes. In this article, we study how to efficiently utilize the green energy supply to fulfill the QoS requirements of multimedia services in a cellular network. Specifically, we study network deployment and power allocation of small cell BSs in a two-tier cellular network in support of high-rate multimedia services. Our objective is to maximize the transmission efficiency while ensuring energy sustainability in green cellular networks powered by green energy sources. For network deployment, we aim to deploy the minimum number of small cell BSs to meet the high throughput demands of multimedia services and statistically guarantee energy sustainability of wireless networks. In addition, a power allocation scheme with cooperative communication is presented to maximize throughput. It is shown that the network sustainability and throughput of green cellular networks can be significantly improved by using the proposed BS placement and power allocation schemes.

INTRODUCTION

The rapid expansion of wireless multimedia services has led to tremendous growth of traffic demand and energy consumption in wireless cellular networks. In order to meet the ever growing bandwidth demands and diverse quality of service (QoS) requirements of multimedia services, it is anticipated that next-generation cellular networks will be a multi-tiered heterogeneous network consisting of macrocell base stations (BSs), microcell BSs, small cell BSs, and mobile users. It has also been reported that the cellular infrastructure has contributed almost 60 percent of the energy consumption of the whole system, even when a BS is idle [1]. In response to the request of reducing energy consumption, and cut the cost of cellular infrastructure operation and management, it is more critical to reduce the energy consumption of the infrastructure compared to wireless terminals. Recent advances in green energy technologies provide an alternative energy source, for example, energy harvested from solar, wind, and so on, to power wireless network infrastructure and achieve a sustainable green radio communication network. Although green energy provides clean and sustainable energy supplies for network devices and causes the minimum detrimental threats to the environment, it is very challenging to efficiently exploit green energy sources to provide ubiquitous multimedia services in cellular networks. This is because unlike stable energy supplies from the electricity grid, the availability and capacity of green energy harvested from natural resources are highly dependent on the deployment environment and may vary with time. When the harvested energy cannot sustain the multimedia traffic demands, service provisioning is interrupted and users experience degraded QoS. Therefore, the most important fundamental design criteria in such a green cellular network is to ensure the energy sustainability of the cellular infrastructure (i.e., that the harvested energy can sustain the network demands.

It is of critical importance for cellular networks to provision quality multimedia services. There are several existing works aimed at minimizing the power consumption and in the meantime ensuring the high-bit-rate transmission of video traffic in traditional cellular networks. In [2], a power optimization algorithm was proposed to achieve the desired throughput with the minimum transmission power, using a truncated hybrid automatic repeat request (HARQ) technique with Chase combining. In [3], an energy minimizing policy is designed for video transmissions over slow Rayleigh fading channels to ensure timely and reliable video transmission. These works studied video services over traditional cellular networks powered by the electricity grid. Recently, green radio communication networks powered

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by sustainable energy sources have provided a promising method to sustain the network performance, which have raised much attention in both industry and academia. Huawei has introduced a site energy solution that combines solar and diesel to help Safaricom change their diesel-powered BSs [4]. After site renovation, the green solution not only provides clean energy, but also reduces the diesel consumption by more than 95 percent, and saves the cost of fuel transportation and maintenance by over 90 percent. Some recent research papers [5–7] have investigated the network planning and resource management issues in green communication networks with sustainable energy supplies. For example, in [5], an analytical framework was developed to analyze the energy sustainability performance of network devices, considering the dynamic energy charging and discharging processes. Based on the analytical model, a resource management scheme was proposed to properly distribute the traffic loads across the network, such that the energy sustainability performance of the network is maximized or, equivalently, the probability that a network device depletes the energy is minimized. In [6, 7], network device placement problems were revisited under the energy sustainability constraint in a green wireless network. Specifically, optimization problems of green BS placement and sub-carrier allocation were formulated to place the minimal number of green BSs (i.e., BSs powered by green energy) in the optimal locations to guarantee that the users' bandwidth requirements and communication energy demands can be satisfied. In addition to energy sustainability, energy efficiency has been one of the main performance metrics in the design of communication and network protocols. In [8], it is shown that efficient cooperative communication can improve both users' throughput and energy efficiency in wireless networks with sustainable energy. By jointly allocating transmission power and deploying green access points (APs), users' throughput can be optimized under the energy sustainability constraints of green APs. However, these research works either aim to improve the energy sustainable performance of wireless networks powered by green energy sources, or study energy-efficient communication and networking solutions to achieve a green radio communication network. To further enhance the sustainable network performance of a green communication network, it is better to consider both energy sustainability and energy efficiency in network planning and resource management.

In this article, we study energy-aware network placement and cooperative communication in a two-tier green cellular network to improve both energy sustainability and energy efficiency, where the macrocell and small cell BSs are powered by sustainable energy sources. To satisfy the multimedia throughput requirements of users with harvested green energy, two steps (i.e., the minimum small cell BS placement and power allocation with cooperative communication) are considered to improve users' throughput. In the first step, our objective is to guarantee the energy sustainability and fulfill the basic multimedia throughput requirements of users in green cellular networks. Specifically, the minimum number of green small cell BSs are deployed to satisfy users' basic multimedia QoS requirements while ensuring energy sustainability constraints based on the charging statistics. In the second step, our objective is to optimize both energy efficiency and energy sustainability. By letting the macrocell BSs or deployed small cell BSs cooperatively transmit with the wireless users to improve the energy transmission efficiency, we further improve the performance of the two-tier green cellular network to fulfill high-end multimedia throughput requirements of users. We show that by allocating the optimal power levels at the cooperative transmitters, the maximum network throughput can be achieved while ensuring the energy sustainability constraint.

Small Cell BS Deployment in Two-Tier Green Cellular Networks

In traditional cellular networks, users are associated with and directly served by macrocell BSs. With the explosive growth of network density and multimedia traffic demand, such network architecture may not be able to fulfill the explosively increasing demand of ubiquitous multimedia services [9]. It was also found in [10] that network capacity can be significantly improved by deploying relay nodes or small cell BSs to forward users' traffic to macro BSs. Therefore, there is growing interest in industry to construct two-tier cellular networks with heterogeneous small cells. In cellular networks with traditional energy, the network planning problem can be formulated as an optimization problem to find the optimal deployment of network devices such that users' multimedia QoS requirements can be fulfilled with the minimum deployment cost. The problem can be further divided into two cases, the continuous case and the discrete case, according to the geographic scenarios. In the continuous case, the network devices can be deployed at any position inside the network region. Problems of this kind can be solved by some traditional optimization algorithms, such as direct search and quasi-Newton methods. In the discrete case, by considering a more realistic network scenario with geographic constraints, the network devices can only be placed at some candidate locations.

However, different from traditional cellular networks, minimizing energy consumption is no longer the most critical concern in green cellular networks, since green energy can provide sustainable clear and replenished energy from natural resources. Instead, the energy sustainability constraint (i.e., the harvested energy should be sufficient to sustain the network operations and users' multimedia QoS requirements) should be considered in green cellular networks. Thus, the fundamental research issues in green cellular networks, such as BS deployment, should be revisited by considering the energy sustainability constraint. Nevertheless, since green energy is highly dependent on local weather, time, and position, its dynamic characteristic makes the BS placement problem challenging. To solve the problem, one of the methods is to estimate the energy charging capability based on the charging statistics. In this context, we aim at deploying the minimum number of green small cell BSs to satisfy users' multimedia QoS requirements while ensuring the energy sustainability of green network devices based on the energy charging capability.

We consider a two-tier green cellular network, where the lower tier consists of small cells e.g., femtocells), and the upper tier is composed of macrocells, such as fourth-generation (4G) Long Term Evolution (LTE). In the lower tier, small cell BSs serve mobile users; in the upper tier, macro BSs provide wireless services for both mobile users and small cell BSs. An example is shown in Fig. 1, where small cell BSs can be installed in some buildings, which are referred to as candidate locations. Generally, as more green BSs are deployed in the network, more energy sources can be used to support high-quality multimedia services in green cellular networks. The transmissions of users are scheduled by a central scheduler (i.e., BSs) in a time-division multiple access (TDMA) fashion to ensure the fairness and QoS performance of users. Orthogonal channels are allocated to different BSs, and there is no intercell interference.

In order to ensure energy sustainability, we aim to deploy the minimum number of small cell BSs in the candidate locations to fulfill the users' basic multimedia throughput requirements with harvested energy based on charging statistics. Let M, S, U, and V denote the set of macrocell BSs, small cell BSs, users, and the set of all nodes in the network, respectively, where $V = M \cup S \cup U$. The set of candidate locations is C, and small cell BSs can only be deployed on these candidate locations due to realistic geographic constraints. Given candidate locations and statistics of energy charging, the small cell BS deployment problem in green cellular networks can be formulated as follows:

$$
\begin{aligned}
&\textit{Minimize} \quad |S| \\
&\textit{Subject to}: s \in C, && \forall s \in S \\
&\qquad \sum\nolimits_{x \in S \cup M} e_{ux} = 1, && \forall u \in U \\
&\qquad \sum\nolimits_{m \in M} e_{sm} = 1, && \forall s \in S \\
&\qquad e_{ij} \in \{0,1\}, && \forall i, j \in V \\
&\qquad \beta_{ux} \geq \beta'_{ux}, && \forall e_{ux} = 1, x \in S \cup M \\
&\qquad \mathcal{E}'^{+}_{x} \geq \mathcal{E}^{-}_{x} && \forall x \in S \cup M
\end{aligned}
\tag{1}
$$

In Eq. 1, the objective is to deploy the minimum number of green small cell BSs into the green cellular networks consisting of green macrocell BSs and users. The first constraint indicates that the small cell BSs can only be deployed in the candidate locations. The second and third constraints show that each user should be served by one BS, and each small cell BS can only connect to one macrocell BS, while the network should be fully connected. In the fourth constraint, if node i is associated with node j, we set $e_{ij} = 1$ and $e_{ij} = 0$ otherwise. The fifth constraint guarantees that the achievable rate between a user and its BS, β_{ux}, should be sufficient to fulfill the multimedia throughput requirement of this user, β'_{ux}. Finally, the last constraint ensures that the approximated energy charging capability should be able to support the energy consumption of the BSs, $\mathcal{E}^{-}_{x}$, to satisfy the users' multimedia throughput requirements, where the energy charging capability from historical data is denoted as $\mathcal{E}'^{+}_{x}$.

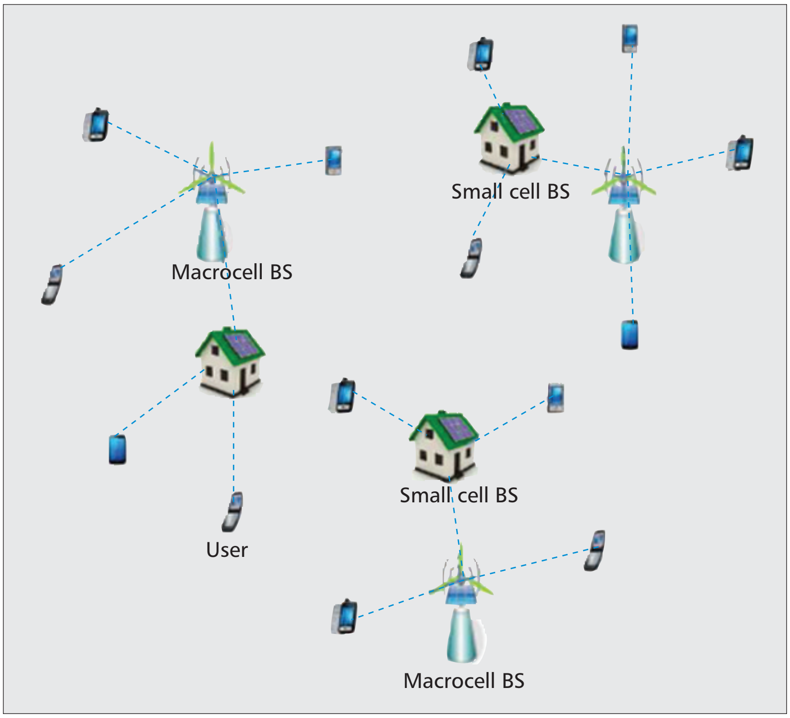

Figure 1. An example of two-tier green cellular networks

Notice that the energy consumption of data transmissions is usually related to the throughput of users in a fixed network (i.e., more energy is required for a higher data rate transmission). In a green cellular network, when the charging capability of the macrocell BSs is not sufficient to sustain the multimedia throughput requirements of all the users, small cell BSs can be placed to help relieve the burden of macrocell BSs and increase the throughput of users. Generally, by deploying small cell BSs to relay the traffic between users and macrocell BSs, users can achieve higher throughput, and the energy consumption at macrocell BSs can be reduced. However, our formulated small cell BS placement problem is a mixed integer nonlinear programming problem (MINLP), which is NP-hard as proved in [11], and we cannot find an efficient polynomial-time solution to address the problem in general. Therefore, we analyze the key parameters that have impacts on the throughput and energy sustainability constraints, and then design efficient heuristic algorithms to achieve good performance. In the formulated problem, we can find that the energy sustainability of macrocell BSs and the multimedia throughput requirements of users are highly dependent on the relative location of the small cell BSs. If small cell BSs are deployed close to macrocell BSs, the energy consumption of macrocell BSs can be significantly decreased to improve the energy sustainability, but the throughput gain for users is little as the distance from users to small cell BSs has no big difference from that of macrocell ones. If small cell BSs are placed near users, the users' throughput can be improved a lot by communicating with close small cell BSs, but the energy sustainability

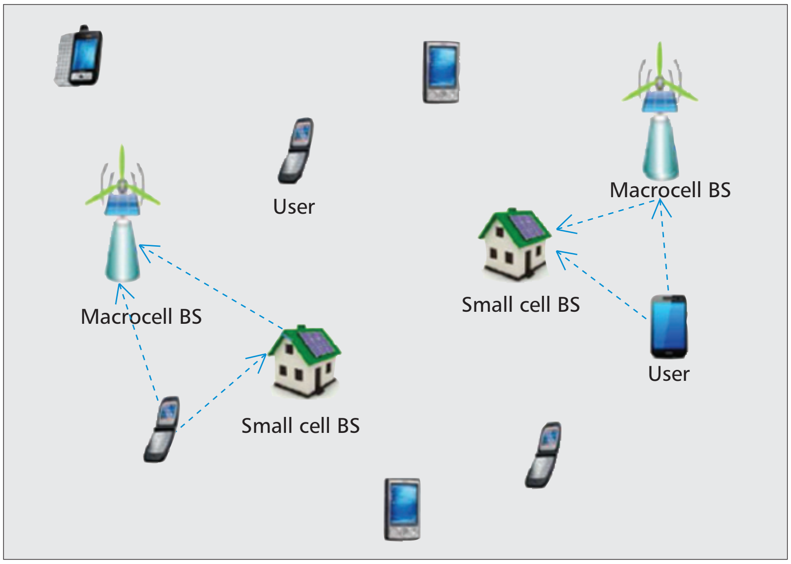

Figure 2. An example of two-tier green cellular networks with cooperative communication.

of macrocell BSs may not be guaranteed since the distance between macrocell and small cell BSs is large. Therefore, an efficient heuristic algorithm should well balance the energy sustainability of macrocell BSs and the throughput gain of users. The number and location of green small cell BSs should be determined by jointly considering the energy sustainability and throughput constraints.

Cooperative Communication in Two-Tier Green Cellular Networks

Generally, by deploying more small cell BSs in the green cellular network, network throughput can be increased, and the energy sustainability performance can be enhanced. However, small cell BS deployment is based on the long-term energy charging statistics at candidate locations instead of the instantaneous energy charging rate. In addition, some multimedia services, such as layered video, have different levels of multimedia QoS requirements. Therefore, it is always desirable to further improve the network sustainable performance by exploiting energy-efficient communication techniques. As a promising technology, cooperative communication can help enhance the network performance and provide better services to users. By letting other nodes help relay transmissions, cooperative communication can significantly improve the network throughput with the broadcast nature of wireless channels. Thus, it is beneficial to apply cooperative communication in green cellular networks to improve the network performance and multimedia QoS [12].

Following the network scenario of small cell BS deployment above, we consider two-tier green cellular networks consisting of users, and small and macrocell BSs, where the lower tier is composed of small cells and the upper tier consists of macrocells. Users are served by green BSs, and green BSs are associated with a rechargeable battery as an energy buffer. Each user can communicate with its BS, and it can make transmissions with other users if they can communicate to each other, such as in device-to-device communication. For each cooperative transmission, a source node can ask BSs to help relay the traffic. To maintain fairness among users, BSs schedule the time period of transmissions for users by TDMA in a synchronized manner. For different BSs, orthogonal channels are used to avoid interference, where under the scenario of cooperative communication a three-terminal relay channel is formed as the transmission channel. To prevent network outage due to some extreme weather, a backup energy source like a mini power generator is equipped for providing temporary energy support when the harvested energy is not enough. An example of two-tier green cellular networks with cooperative communication is shown in Fig. 2. In general, two cooperative protocols can be used, amplify-and-forward (AF) and decode-and-forward (DF). Compared to AF, DF can completely eliminate the noise, as cooperative relay decodes the signal before forwarding it. Thus, we use DF for cooperative transmission to improve the spectral efficiency, since the source and cooperative relay are able to transmit at the same time and on the same frequency band.

By using cooperative communication, single-hop and long-distance transmission is changed to two-hop and short-range transmission. In order to evaluate the performance of cooperative communication in green cellular networks, we need to derive the expression of the achievable rate for each cooperative transmission. Let x_{s_i}, y_{d_i}, y_r, and x_r denote the input to the channel, the output of the channel, the observation by the cooperative relay, and the input symbol chosen by the cooperative relay, respectively. The maximal achievable rate of the discrete memoryless DF relay channel can be expressed as $R^{(i)} \le \max_{p(x_{s_i}, x_r)} \min\{R_r, R_d\}$, where the first item $R_r = I(X_{s_i}; Y_r|X_r)$ is the largest rate for cooperative relay to decode the signal, and the second item $R_d = I(S_{s_i}, X_r; Y_{d_i})$ guarantees that the signal can be successfully decoded by the destination. Let $h_{s_i r}$, h_{s_i}, and $h_{s_i d_i}$ denote the channel gain coefficients to represent the channel conditions for source-relay, relay-destination, and source-destination, respectively. Suppose that all wireless channels are independent Rayleigh fading channels with path loss, and all channel gain coefficients can be estimated accurately at the BSs. We can further derive the highest achievable rate of the relay channel in Eq. 2, where σ^2, $P_s^{(i)}$, and $P_r^{(i)}$ denote the variance of zero-mean Gaussian noise, and the maximum transmission power of the source node and cooperative relay for channel i, respectively.

$$
\begin{aligned}
R^{(i)} &= \max_{0\le\beta\le1} \min(R_r, R_d\},\\
R_r &= f\left(\left|h_{s_i r}\right|^2 \beta P_s^{(i)}\right)\\
R_d &= f\left(\left|h_{s_i d_i}\right|^2 \beta P_s^{(i)} + \left(\left|h_{s_i d_i}\right|\sqrt{\bar{\beta} P_s^{(i)}} + \left|h_{rd_i}\right|\sqrt{P_r^{(i)}}\right)^2\right),
\end{aligned} \quad (2)
$$

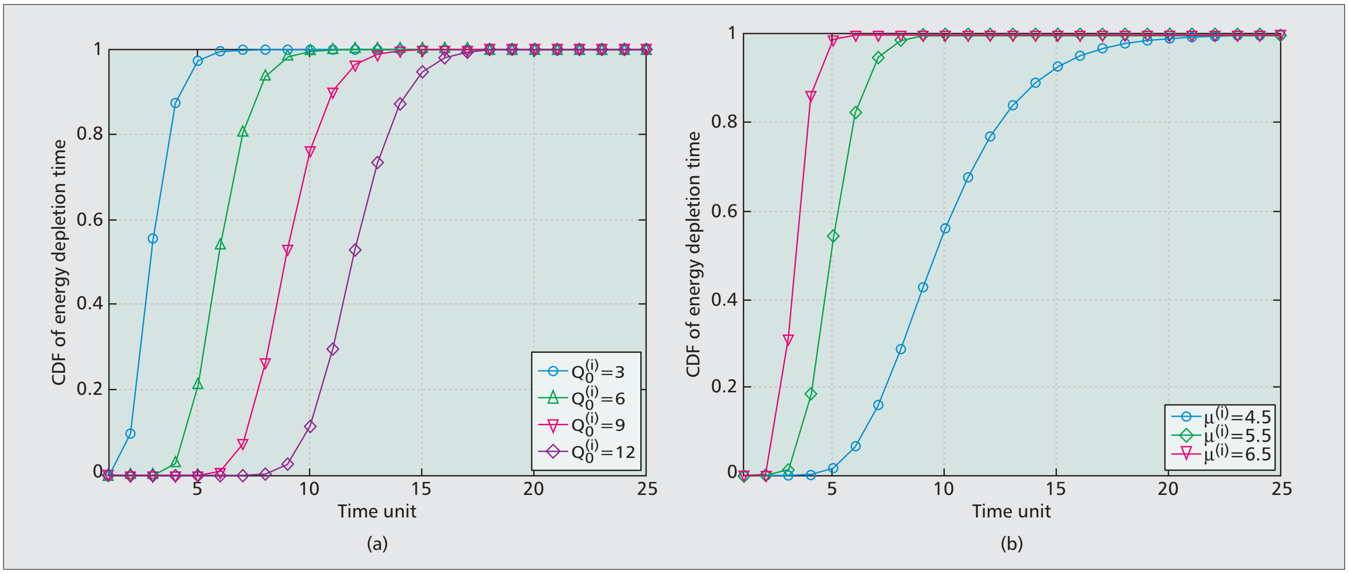

Figure 3. CDF of energy depletion time: a) $\lambda^{(i)} = 3.5, \mu^{(i)} = 5.5$; b) $Q_0^{(i)} = 10, \lambda^{(i)} = 3.5$.

where $f(x) = 1/2 \log(1 + (x/\sigma^2))$. The total transmission power $P_s^{(i)}$ is divided into two parts, $\beta P_s^{(i)}$ and $\bar{\beta} P_s^{(i)}$, adjusted by the collaboration coefficient β. As we can observe from Eq. 2, $P_s^{(i)}$ and $P_r^{(i)}$ determine the achievable rate $R^{(i)}$ when the cooperative relay is fixed for each cooperative transmission. Thus, we can maximize the achievable rate of each cooperative transmission by optimally controlling the transmission power.

Power Allocation with Dynamic Energy Buffer

Since green BSs are used to relay traffic in cooperative communication, we should analyze the dynamic characteristics of green energy and guarantee the energy sustainability of cooperative relays. We model the dynamic energy charging process as a non-homogeneous random process, where the charging rate is $\lambda(t)$. As each transmission occupies a very short period, the charging rate during channel i's transmission can be approximated as constant $\lambda^{(i)}$. The energy consumption rate is considered as a constant $\mu^{(i)}$ during each cooperative transmission. By approximating the charging process as a Wiener process [13] and applying the method in [14] through Fourier transform, we can obtain the probability density function of the energy depletion time as

$$f_D\left(t; Q_0^{(i)}\right) = \frac{Q_0^{(i)}}{\sqrt{4\gamma\pi t^3}} \exp\left\{-\frac{\left(Q_0^{(i)} + \left(\lambda^{(i)} - \mu^{(i)}\right)t\right)^2}{4\gamma t}\right\}, \quad (3)$$

where $Q_0^{(i)}$ and γ denote the initial buffer length and the scaling factor depending on the energy charging capability, respectively. Figure 3 shows the cumulative distribution function (CDF) of energy depletion time with different discharging rate and initial energy of buffer. In Fig. 3a, the normalized average energy charging and discharging rate are set as 3.5 and 5.5, respectively. The CDF curves of the energy depletion time shift right with the increase of initial buffer energy $Q_0^{(i)}$. In Fig. 3b, the normalized initial buffer energy and the average energy charging rate are set as 10 and 3.5. With the increase of energy discharging rate, the CDF curves of energy depletion time decrease rapidly and their slopes have an significant increase.

Based on the analysis of achievable rate and green energy, we aim at maximizing transmission efficiency while ensuring network sustainability. To this end, two common network scenarios are considered:

- Both BSs and users are able to adjust their transmission power, called total power constraint.
- Only BSs can adjust the transmission power, called BS power constraint.

For the former scenario, we can derive the maximum transmission power of the BS on channel i for ensuring energy sustainability based on the expectation of energy depletion time. Then we consider two cases to calculate the optimal transmission power of users:

- The destination decoding rate is the bottleneck, called the synchronous case.
- The relay decoding rate is the bottleneck, called the asynchronous case.

After that, we can derive the optimal transmission power for the user in both the synchronous and asynchronous cases. For the latter scenario, we first derive the transmission power for the BS to achieve the maximum transmission rate. After that, the maximum transmission power of the BS for ensuring the energy sustainability is calculated. Finally, the optimal transmission power is determined as the minimum of the two values. Figure 4 plots the achievable rate under different energy charging rates, where the normalized initial buffer energy is set to be 10. We can observe that in both network scenarios, cooperative communication can significantly improve network throughput.

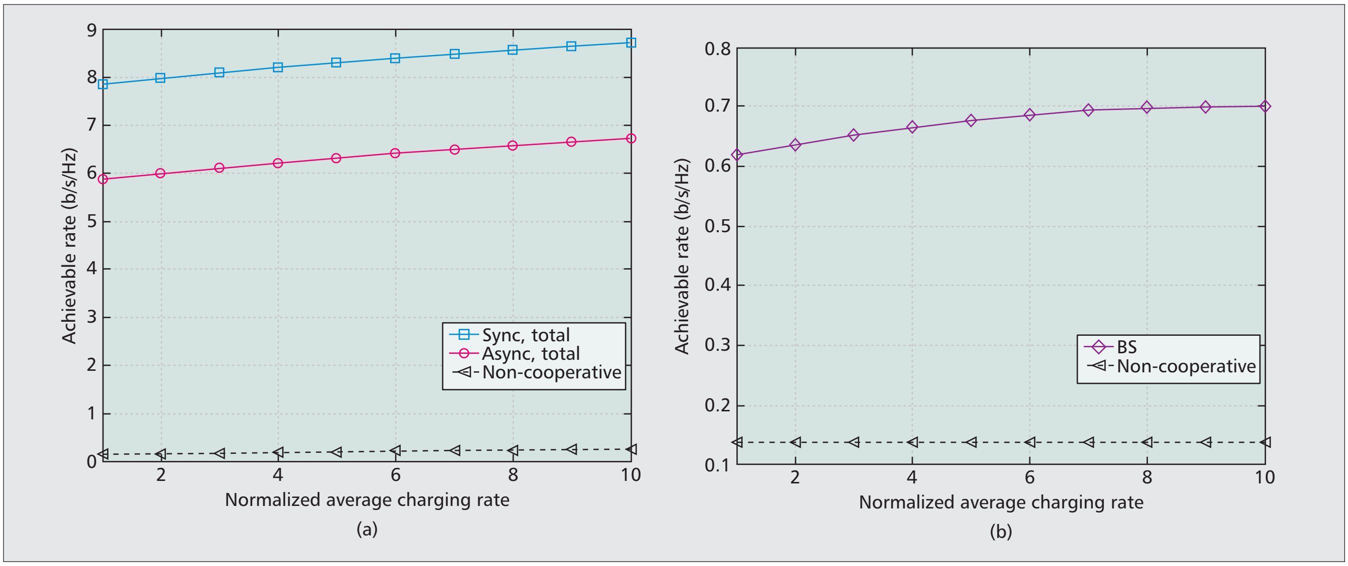

Figure 4. Rate comparison under various charging rate: a) total power constraint; b) BS power constraint.

Conclusion and Future Research

In this article, we have investigated the energy-aware network small cell BS deployment and cooperative communication in a two-tier green cellular network to fulfill the energy and throughput requirement of high-bit-rate multimedia services. We have formulated the minimum node placement problem by considering the throughput and energy sustainability constraints. We further improve the transmission energy efficiency by exploiting cooperative communication techniques in green cellular networks. We have shown that by allocating the optimal power levels of the transmitters based on cooperative communication, the network throughput can be maximized while ensuring the energy sustainability of network devices and satisfactory multimedia QoS of users.

In the future, it is anticipated that more network devices will be powered by sustainable energy, including wireless terminals. How to fully exploit the energy charging capabilities of wireless devices in communication and networking protocol design to fulfill the ever growing multimedia traffic demand remains a challenging and open issue. We present our thoughts on the research directions in this field.

- In green cellular networks where small cell BSs and wireless users are geographically distributed, it is promising to apply multi-user multiple-input multiple-output technology to allow multiple cooperative transmissions. Considering the energy sustainability and multimedia QoS requirement constraints, how to carefully select the appropriate cooperation pairs and jointly optimize power allocation and rate adaptation for cooperative communication is an interesting and challenging research issue.
- In green cellular networks, users are generally mobile and experience handoff from one BS to another when they are downloading multimedia data. In addition, mobile relay in cooperative communication appears to be a cost-effective solution to improve the capacity of cellular networks. How to incorporate the different mobility patterns of wireless users to improve cooperative communication and handoff performance while ensuring the energy sustainability of a green cellular network requires further research.
- Dynamic energy charging and discharging poses great challenges for network resource management in green cellular networks. To achieve a long-term sustainable cellular network, scheme design across multiple layers is needed. For example, physical layer power allocation coupled with medium access control layer scheduling can ensure that various tasks are allocated to appropriate services according to their requirements. Joint power control and scheduling scheme design can help manage the limited network resources to satisfy tasks with a variety of multimedia QoS requirements and guarantee energy sustainability.

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Biographies

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Lin X. Cai is a senior engineer with the U.S. Wireless R&D Center, Huawei Technologies Inc. She received her M.A.Sc. and Ph.D. degrees in electrical and computer engineering from the University of Waterloo in 2005 and 2010, respectively. Before she joined Huawei, she was a postdoctoral research fellow in the Electrical Engineering Department at Princeton University in 2011. Her research interests include green communication and networking, resource management and topology control, broadband multimedia services, and cognitive radio networks.

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