Green-Oriented Traffic Offloading through Dual Connectivity in Future Heterogeneous Small Cell Networks

Yuan Wu, Li Ping Qian, Jianchao Zheng, Haibo Zhou, and Xuemin (Sherman) Shen

The authors overview the green-oriented traffic offloading in future HCNs that exploits the recent advanced energy-technologies including energy harvesting (EH), local energy sharing (ES) enabled by smart grid, and wireless power transfer (WPT). They discuss the challenges in resource management when exploiting EH, ES, and WPT to support traffic offloading, and provide possible solutions.

ABSTRACT

Traffic offloading through small cells has been considered as a promising approach to accommodate tremendous traffic growth in future heterogeneous cellular networks (HCNs). The dense deployment of small cells, however, has led to a growing concern about the excessive carbon-based on-grid energy consumption in HCNs. In this article, we first overview the green-oriented traffic offloading in future HCNs that exploits the recent advanced energy technologies including energy harvesting (EH), local energy sharing (ES) enabled by smart grid, and wireless power transfer (WPT). We then discuss the challenges in resource management when exploiting EH, ES, and WPT to support traffic offloading, and provide possible solutions, especially by using the emerging dual connectivity (DC) in recent 3GPP specifications. Furthermore, we present a case study on the optimal DC-enabled traffic offloading through small cells that are powered by EH, with the objective of minimizing the total on-grid power consumption of all small cells and macrocells. The case study validates the benefit of exploiting the DC feature for traffic scheduling and the harvested energy to reduce the total on-grid power consumption. We finally share our view of some research directions in the green-oriented traffic offloading in HCNs.

INTRODUCTION

The past decade has witnessed an explosive growth of smart mobile devices and popularity of mobile Internet services, leading to tremendous traffic pressure in cellular networks. By exploiting heterogeneous small cells densely underlaid to macrocells, traffic offloading through small cells provides a cost-efficient approach to relieve traffic congestion at macrocells [1]. By bringing radio access networks close to mobile users, traffic offloading through small cells reaps benefits such as enhancing throughput and improving coverage, and thus plays a vital role in supporting various applications in future cellular networks, (e.g., augmented reality, massive machine-type communications, and the Internet of Things [2]. Because of the advantages of traffic offloading, the recent Third Generation Partnership Project (3GPP) specification has proposed the paradigm of small cell dual connectivity (DC) [3], which enables a mobile user, by using two different radio interfaces, to communicate with a macrocell (referred to as the master cell) and simultaneously offload data through a small cell (referred to as the slave cell). The DC enables flexible and dynamic traffic scheduling between the macro and small cells, which improves users' quality of service (QoS) and the efficiency of resource utilization. However, the massive deployments of heterogenous small cells (e.g., femtocells, picocells, and WiFi hotspots) have raised increasing concern about excessive energy consumption, especially the huge carbon-based on-grid energy consumption. Thus, a crucial question is how to effectively reduce the on-grid power consumption for traffic offloading in heterogeneous communications networks (HCNs) while providing satisfactory QoS for mobile users [4, 5]. Many research activities have been carried out to study energy-efficient traffic offloading [6] and data caching at small cells [7].

In addition to relying on on-grid power supply, recent advances in energy technologies, including energy harvesting (EH) [8], local energy sharing (ES) [9, 10], and wireless power transfer (WPT) [11, 12] enable a hybrid power supply to support small cells and mobile users, which yields green-oriented and sustainable traffic offloading. First, by deploying EH devices such as solar panel and wind turbine, macro and small cells are able to actively harvest green energy from the environment for traffic offloading and reduce the on-grid power usage. Second, the emerging paradigm of ES, as an important capability enabled by smart grid with advanced information and communication technologies, allows macro and small cells to form local energy networks in which neighboring cells are able to share locally stored energy (e.g., harvested green energy) and improve the overall energy utilization. Third, the recently advanced WPT, as a promising energy transfer method through RF signal, provides an effective approach to charge mobile terminals (MTs) without requiring power line connection. WPT is very attractive in traffic offloading through device-to-device (D2D) communication [13], since one can use WPT to support the seed-MT, who offloads traffic as a relay for other MTs via D2D links, which thus yields sustainable offloading.

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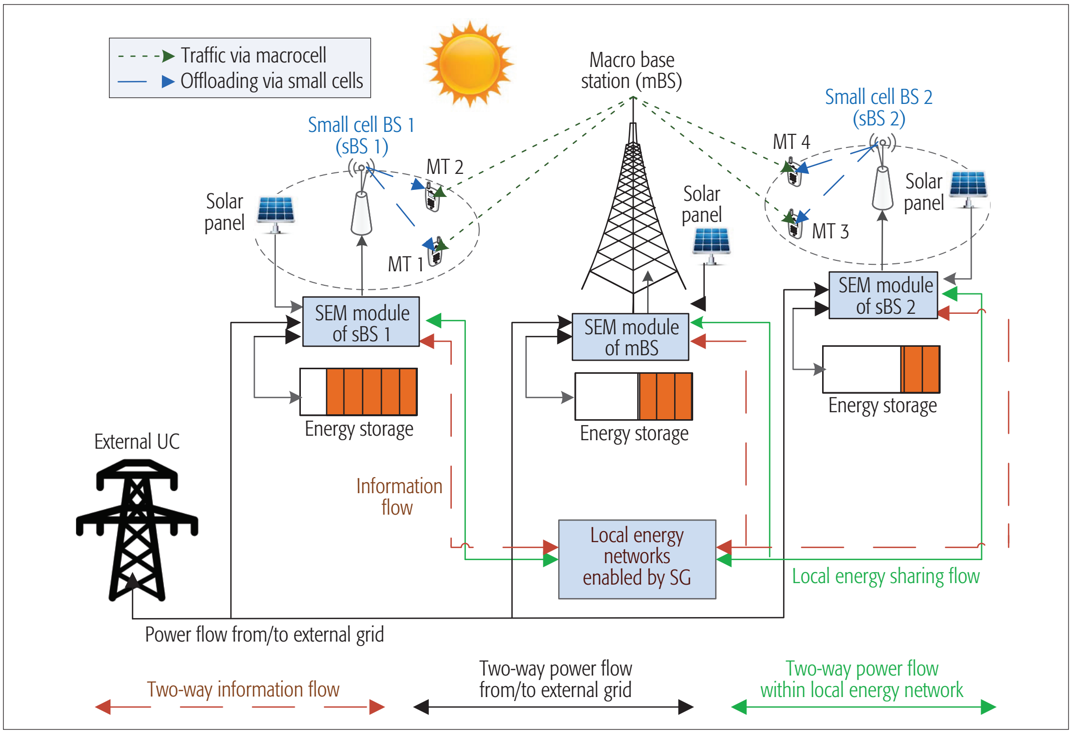

Figure 1. Traffic offloading through small cells assisted by EH/ES.

The past decade has witnessed an explosive growth of smart mobile devices and popularity of mobile internet services, leading to a tremendous traffic pressure in cellular networks. By exploiting heterogeneous small cells densely underlaid to macro cells, traffic offloading through small cells provides a cost-efficient approach to relieve traffic congestion at macro cells.

Despite the potential benefits, the special features in using EH, ES, and WPT to support traffic offloading in HCNs yield new challenges in radio resource management. Thus, this article studies green-oriented traffic offloading, which exploits these advanced energy-technologies.

•We introduce the architecture of green-oriented traffic offloading that exploits the advanced energy technologies including EH, ES, and WPT. Taking into account the new features of power supplies, we illustrate the connections between energy management and traffic offloading that facilitate exploiting EH, ES, and WPT to reduce the on-grid power consumption while providing satisfactory QoS.

•We illustrate the challenges in resource management for traffic offloading that exploits EH, ES, and WPT, with the objective of realizing energy saving and sustainable traffic offloading. We further discuss possible solutions to address these challenges, especially by using the new feature of DC-enabled traffic offloading.

•As a concrete case study, we present optimal DC-enabled traffic offloading through small cells that are powered by EH, with the objective of minimizing the total on-grid power consumption of the macro and small cells. The results validate the benefit of exploiting the DC feature for traffic scheduling and the harvested energy to reduce the total on-grid power consumption while guaranteeing QoS for users.

ARCHITECTURE OF TRAFFIC OFFLOADING ASSISTED BY ADVANCED ENERGY TECHNOLOGIES

This section presents the architecture of traffic offloading that exploits advanced energy technologies (i.e., EH, ES, and WPT), and introduces the smart energy management (SEM) module for the interaction between energy management and traffic offloading. For the sake of easy presentation, we illustrate two architectures, namely, traffic offloading through small cells, which are powered by EH and ES (as shown in Fig. 1), and traffic offloading through MTs' D2D communication, which is powered by WPT and EH (as shown in Fig. 3).

TRAFFIC OFFLOADING THROUGH SMALL CELLS POWERED BY EH/ES

Figure 1 shows the architecture of traffic offloading through small cells that integrate the capabilities of EH and ES. Specifically, each small/macrocell has a hybrid energy supply including:

- The on-grid power supply from external utility companies
- The EH-based power supply through EH devices
- The ES-based power supply from local energy networks in which different cells can flexibly share the locally stored energy

To realize proper management of the hybrid energy supply for traffic offloading, each cell is equipped with a SEM module. The purpose of the SEM module is three-fold. First, accounting for the hybrid and dynamic energy supply (especially the intermittent EH supply), the SEM module monitors the real-time dynamics of the stored energy. Second, the SEM module controls the signaling with the SEM modules of other cells to facilitate the energy sharing within the local energy networks. Third, the SEM module coordinates the energy management and traffic offloading. Specifically, based on the real-time traffic demand and QoS provisioning, the SEM module (together with the neighboring SEM modules) checks whether the required offloading service can be admitted or not. Specifically, we consider the following two cases.

When using EH, the small and macro cells suffer from unreliable power-supply, which has imposed a crucial challenge to traffic offloading. For instance, due to the insufficient power-supply, the EH-powered small cell might not be able to provide the required offloading rate, which leads to a QoS-outage.

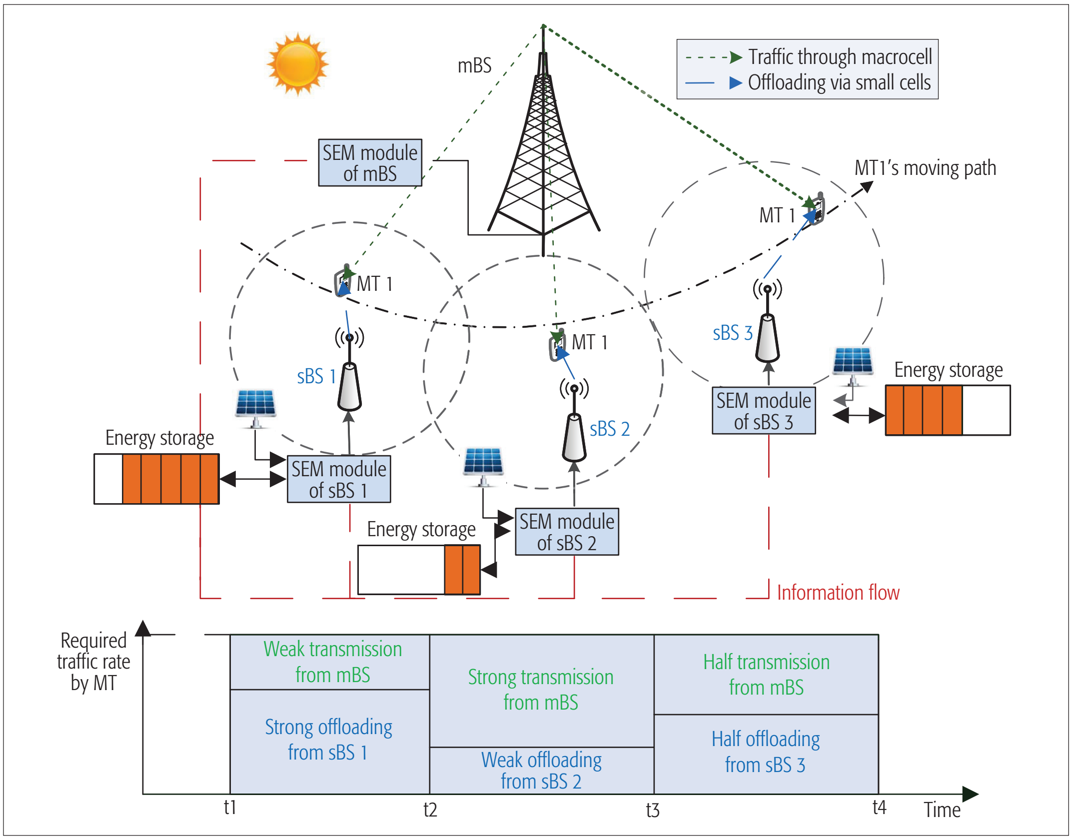

Figure 2. Illustration of traffic offloading through EH-powered small cells 1-3 when MT 1 moves across the cells.

Traffic Offloading with Guaranteed QoS: Given the offloading request with specified QoS (e.g., offloading rate and delay), the SEM module ensures that the small cell has a sufficient energy supply to provide the required offloading service. As shown in Fig. 2, accounting for the mobility of MTs, the SEM module needs to coordinate with the neighboring cells' SEM modules to guarantee that the neighboring cells have sufficient energy supplies to provide a sustainable offloading service when the MT is moving across the cells. Moreover, with the DC, the SEM module of the small cell collaborates with that of the macrocell to properly split the MT's traffic, such that both the small and macrocells are able to support the required offloading rate.[1]

Traffic Offloading without QoS Guarantee: When QoS-provisioning is elastic, the SEM module, based on the available energy status of the small cell, interacts with the offloading management module to realize an energy-aware and adaptive traffic offloading for the targeted MT.

OFFLOADING VIA D2D-COMMUNICATION ASSISTED BY WPT/EH

Figure 3 illustrates the architecture of traffic offloading through the MTs' D2D communication, which integrates the capabilities of WPT/EH. In traffic offloading through MTs' D2D communication, some seed MTs first receive data from the macro base station (mBS) through a cellular link and then offload the received data to other MTs through D2D links, thus effectively migrating traffic from the cellular link to the D2D link. However, such offloading will quickly drain the seed MTs' batteries. Exploiting WPT/EH to charge the seed MTs is an effective approach to address this issue. First, the macrocell can use WPT to charge the seed MTs via the cellular link; that is, part of the RF signal power is dedicated to charging the seed MTs, while the rest is dedicated to traffic delivery. Second, the seed MTs, by using the advanced EH devices, can also actively harvest green energy from the environment.

To facilitate energy management and coordinate with traffic offloading, each MT is equipped with the SEM module whose purpose is two-fold. First, considering the energy supply from WPT/EH, the SEM module monitors the MT's energy dynamics in real time and facilitates the MT's offloading operation. Second, the SEM module controls the signaling with neighboring MTs' SEM modules, such that the MTs are aware of the neighboring MTs' energy status and collaboratively execute the D2D-assisted traffic offloading (notice that the D2D communication can also facilitate the two-way communication among different MTs). Depending on different types of QoS provisioning, we consider the following two cases.

Offloading through D2D Communication with Guaranteed QoS: Given the offloading request with specified QoS requirement, the seed MT's SEM module determines whether it has sufficient energy to provide the offloading service or not. If not, by coordinating with the neighboring MTs' SEM modules, the seed MT short of energy can either notify the mBS for charging with WPT, or notify other neighboring MTs with sufficient power to act as the seed MT to execute offloading.

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[1] The operations of DC require additional signaling overhead for coordination between the macro and small cells, which can be supported by current small cells' backhaul connections.

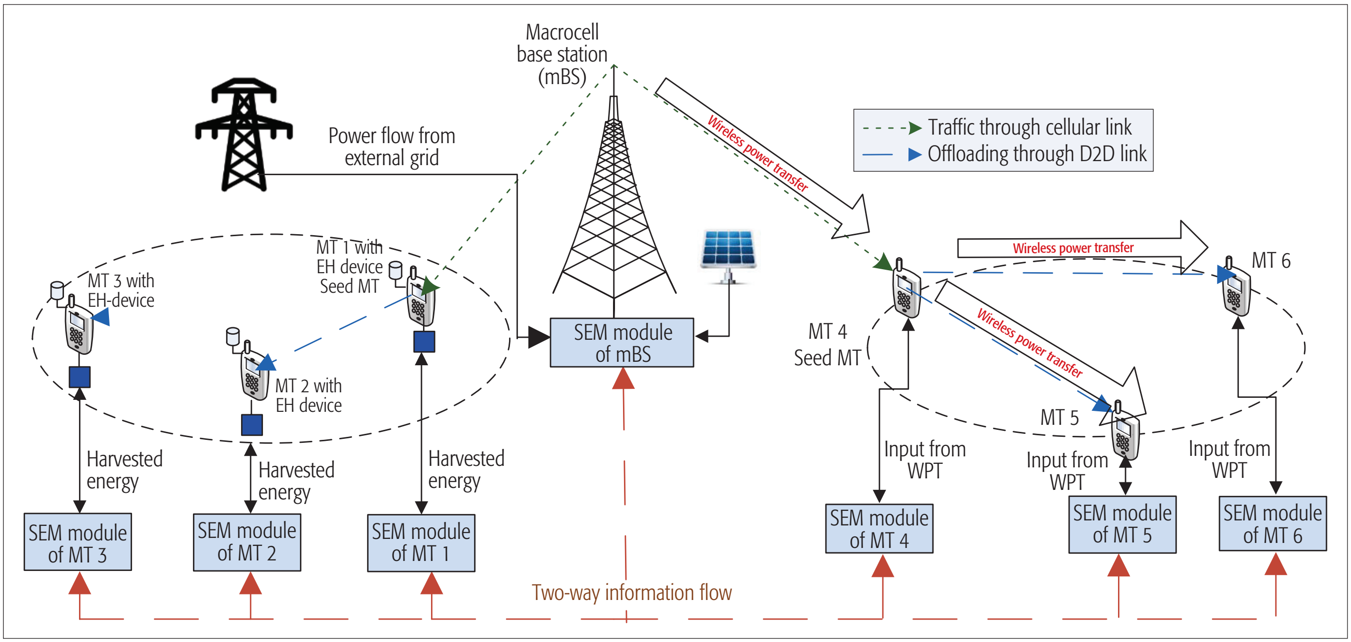

Figure 3. Traffic offloading via D2D communication assisted by WPT/EH.

Offloading through D2D Communication with Elastic QoS: When the QoS provisioning is elastic, the MTs' SEM modules, based on their energy status, interact with the traffic offloading management to execute energy-aware and adaptive traffic offloading. For instance, a seed MT with a low energy supply can slow down the offloading rate until it becomes sufficiently charged. Moreover, through coordination, the MTs are aware of their respective energy usages and adaptively act as seed MTs to improve the overall fairness in energy consumption.

Although Fig. 3 focuses on downlink traffic offloading, WPT/EH can also be used to support the MTs' uplink traffic offloading toward small and macrocells, since WPT/EH provides an effective approach to charge the MTs' batteries to prolong their operations.

CHALLENGES IN EXPLOITING ADVANCED ENERGY TECHNOLOGIES FOR TRAFFIC OFFLOADING

We further discuss the challenges in exploiting EH, ES, and WPT to support traffic offloading, with the objective of reducing the on-grid power consumption and realizing sustainable offloading. Table 1 highlights the comparison between different energy supplies based on EH, ES, and WPT, from the perspectives of supply intermittency, supply efficiency, mobility support, and hardware requirement.

The comparison in Table 1 indicates that, from the perspective of MTs, it is preferable to use WPT to charge MTs due to the strong mobility support and the low-cost transceiver circuits for transferring/collecting RF energy. In comparison, from the perspective of network infrastructure, it is preferable to use EH/ES to support small and macrocells, since ES and EH require costly infrastructures (e.g., power grid connections, smart meters, and large numbers of EH devices). Thus, in the following, we focus on three detailed cases to illustrate the challenges when exploiting EH, ES, and WPT, namely, traffic offloading through small cells powered by EH, traffic offloading through small cells assisted by ES, and traffic offloading through MTs' D2D communication powered by WPT.

	Intermittency	Supply efficiency	Mobility wupp.	Hardware req.
EH	High	Low	Medium	EH device
ES	Low	High	Low	ES infrastructure
WPT	Medium	Low	High	WPT circuit

Table 1. Features of power-supply based on EH, ES, and WPT.

TRAFFIC OFFLOADING THROUGH SMALL CELLS POWERED BY EH

When using EH, the small and macrocells suffer from unreliable power supply, which has imposed a crucial challenge to traffic offloading. For instance, due to the insufficient power supply, the EH-powered small cell might not be able to provide the required offloading rate, which leads to a QoS outage. We illustrate the key issues and the potential solutions as follows.

Dynamic Offloading Strategy: Viewing the time-varying and unreliable EH supply, a crucial question is how to exploit the EH supply to reduce the on-grid power consumption in traffic offloading, while addressing the negative influence such as QoS outage. In addition to conventional adaptive cell operations such as on/off mode and cell zooming [14, 15], dynamic scheduling of the offloaded data in the temporal/spatial domain provides an effective approach to address this question. For instance, as shown in Fig. 4, with DC, the macrocell can actively provide more traffic to avoid QoS outage when the small cell suffers from a low EH supply. System information, including the arrival rate of EH, traffic intensity, channel information, and delay tolerance, can all be utilized for dynamic offloading.

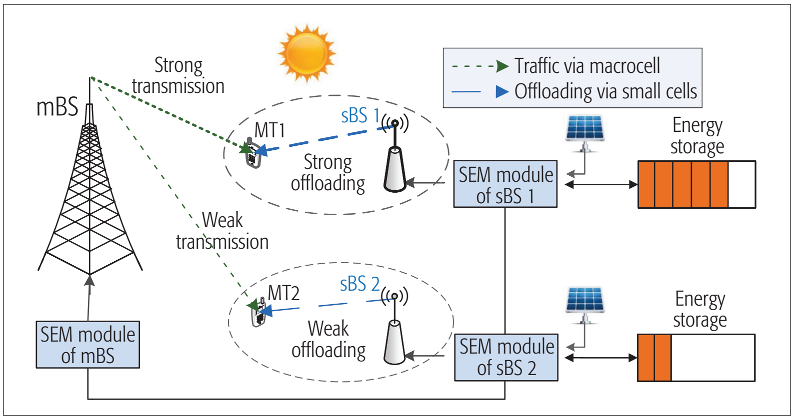

Figure 4. Dynamic offloading assisted by DC based on the sBSs' energy availability.

Delay Tolerance: Many mobile Internet services show delay tolerance of different levels, which can be exploited for dynamic offloading according to the time-varying EH supply. Specifically, by exploiting the delay tolerance, a small cell can actively delay the offloading until the small cell collects sufficient energy. Moreover, the small cell can use some economic approaches (e.g., pricing) to incentivize the MT to tolerate a longer delay, such that the small cell can collect more EH supply and reduce the on-grid power consumption. Meanwhile, the MT receives additional reimbursement for suffering from the longer delay, which eventually yields a win-win outcome for the small cell and the MT.

Backhaul Capacity: The backhaul capacity is an important factor that limits the performance of traffic offloading, even though the considered small cell has a sufficient energy supply. (In the context of HCNs, the backhaul refers to the link between small cells and core networks.) Due to the limited bachaul capacity, severe congestion and delay will occur when many MTs aggressively offload traffic through the same small cell. Hence, dynamic offloading needs to jointly take into account the small cells' energy availability and the backhaul capacity to fully exploit the EH supply and the backhaul capacity.

Co-Channel Interference: Due to reusing the frequency channels among different small cells, there might be severe co-channel interference among the offloading links of neighboring cells, which degrades the overall offloading performance (e.g., energy efficiency and throughput). Thus, the dynamic offloading needs to take into account and mitigate such co-channel interference (e.g., by properly scheduling the traffic offloading of two neighboring cells that have "strong" EH supplies).

Energy Sustainability and Performance Trade-off: Due to the intermittent EH supply, it is crucial to characterize the energy sustainability of the small cell in trading with QoS provisioning (e.g., offloading rate and service outage). The energy sustainability characterizes the sustainable duration of a small cell when it offloads traffic for the MTs with specified QoS. Aggressively offloading traffic through one cell will quickly drain the cell's energy storage and degrade the energy sustainability. From the network perspective, it is important to investigate how to optimize the QoS experience in offloading while satisfying the required energy sustainability. Two approaches to address this issue are as follows.

Offloading with Traffic Scheduling: The first approach is to properly offload the MTs' traffic toward different cells by taking into account different cells' available energy levels, such that we can balance the traffic load and energy consumption among different cells to improve the energy sustainability of the whole network.

Spectrum-Energy Trade-off: The second approach is to trade spectrum efficiency for energy efficiency. Offering the small cells with a larger bandwidth for offloading traffic can effectively reduce the energy consumption, which, however, sacrifices the spectrum efficiency. Fortunately, the recently advanced non-orthogonal multiple access (NOMA), which enables the reuse of the same frequency channel for many users, provides a promising approach to simultaneously enhance the energy efficiency and spectrum efficiency in traffic offloading.

Traffic Offloading through Small Cells Assisted by ES

Thanks to the advanced paradigm of smart grid, ES is envisioned to effectively improve the energy efficiency of cellular systems. With ES, a group of neighboring small/macrocells can form a local energy network in which they can cooperatively share the locally stored energy (e.g., the harvested green energy) to improve the overall energy utilization. However, how to realize the local energy sharing network has imposed a challenge. Two viable approaches are illustrated as follows. (In practice, the small cells' SEM modules can act as the local controller in a local energy network to coordinate the following energy sharing management.)

Direct Energy Sharing via Energy Transfer: The first approach is direct energy sharing; that is, cells with extra energy supply but low traffic pressure can actively transfer energy (via power line connection) to the cells with low energy supply, such that the cells together can make efficient utilization of the locally stored energy and satisfy the mobile users' (MUs') traffic demands. However, due to being at the distribution level, direct energy transfer among different cells incurs a non-negligible energy transfer loss. Thus, we need to take into account the energy transfer loss and design a proper energy scheduling scheme to fully exploit the available energy in the local energy network.

Indirect Energy Sharing via Offloading Scheduling: Another approach is indirect energy sharing via offloading scheduling: the cell with low energy supply actively offloads the MTs' traffic to the cell with sufficient energy supply, with the objective of balancing energy usage. In particular, such an operation can be realized by increasing the transmit power for the pilot signal of the host cells that have sufficient energy supply to increase the cell coverage. However, a critical issue is the home user's QoS protection. When offloading too much traffic from other cells, the home users in the host cells might suffer from degraded QoS performance (e.g., longer traffic delay) due to the increased traffic load. We thus need to properly design the offloading scheduling to mitigate the energy imbalance while accounting for the home users' QoS degradation.

TRAFFIC OFFLOADING THROUGH MTS' D2D-COMMUNICATION POWERED BY WPT

In traffic offloading through D2D communication, the seed MTs consume more power to offload other MTs' traffic and thus quickly use up the stored energy. Using WPT to charge the seed MTs (as shown in Fig. 3) provides an effective approach to charge the seed MTs and realize sustainable offloading service. However, several important issues need to be taken into account.

Energy Transfer Efficiency and Selection of Seed MTs: Due to the radiation of RF signal, using WPT to charge the seed MTs suffers from low energy transfer efficiency. For instance, a significant amount of the delivered energy will be lost if the selected seed MTs are far away from the energy transmitter. Thus, we need to jointly consider the energy transfer efficiency and traffic delivery efficiency when choosing the seed MTs, such that a severe energy transfer loss can be avoided, and the selected seed MTs can efficiently offload traffic for other MTs.

Joint WPT and Offloading Management: There is a coupling effect between allocating radio resource for executing WPT and that for offloading traffic. Specifically, executing WPT requires orthogonal radio resource (e.g., in the power/time domain) with that for traffic delivery. Hence, proper resource management is required for executing WPT and traffic offloading, such that the seed MTs can have suitable amounts of energy to offload traffic with satisfactory QoS. Neither too aggressive WPT nor too conservative WPT is desirable. Specifically, aggressive WPT to the seed MTs sacrifices the available resource for data delivery, which impairs the traffic rate from the macrocell and results in unnecessary redundant energy transfer. However, conservative WPT results in energy shortage at the seed MTs, which limits the seed MTs from providing satisfactory offloading service.

Incentive Design Based on WPT: A practical issue in traffic offloading through D2D communication is the incentive design for providing offloading service; that is, the seed-MTs are aware of the social tier with other MTs and prefer to offload traffic for those MTs with strong social tiers. Hence, active WPT for the seed MTs provides an approach to enhance the social tier, and yields incentive-based traffic offloading through D2D communication. Specifically, MTs who want to receive the offloading service from the seed MT first use WPT to charge the seed MT to strengthen their respective social tiers with the seed MT. Based on the established social tiers, the seed MT then provides different offloading rates for the corresponding MTs.

AN OPTIMAL DESIGN OF DC-ENABLED TRAFFIC OFFLOADING THROUGH EH-POWERED SMALL CELLS

As a case study to validate the advantage of exploiting the DC feature and EH supply, we present optimal DC-enabled traffic offloading through EH-powered small cells, with the objective of minimizing the total on-grid power consumption. Specifically, we consider that a group of small cell base stations (sBSs) $\mathcal{S}$ are underlaid to the coverage of an mBS. The sBSs (together with the mBS) provide DC-enabled downlink traffic offloading for a group of MTs $\mathcal{I}$. The mBS is powered by on-grid energy, and each sBS is powered by both on-grid energy and EH. Each MT is associated with the mBS, and the sBSs select different MTs to provide DC-enabled offloading. To model this selection, we use the binary variable $z_{si} = 1$ to denote that sBS *s* selects MT *i* to provide the offloading service, and $z_{si} = 0$ means the opposite. Supposing that $z_{si} = 1$, then sBS *s* offloads part of MT *i*'s traffic demand, and the mBS provides the remaining part to satisfy MT *i*'s traffic demand. Since each sBS uses both the on-grid power supply and EH supply, we use p_{si} to denote sBS *s*'s transmit power to MT *i* from its on-grid power supply, and we denote sBS *s*'s EH supply by Q_s (i.e., a random variable due to the intermittency of EH), which is shared by all MTs selected to serve. Thus, the offloading rate from sBS *s* to MT *i* is

$$x_{si} = W_s \log_2\left(1+\frac{\left(p_{si}\sum_{i\in\mathcal{I}} z_{si}+Q_s)g_{si}\right)}{n_{si}\sum_{i\in\mathcal{I}} z_{si}}\right) z_{si}, \qquad (1)$$

where $\sum_{i\in\mathcal{I}} z_{si}$ denotes the number of MTs served by sBS *s*, W_s denotes sBS *s*'s channel bandwidth, and g_{si} denotes the channel power gain from sBS *s* to MT *i*. Notice that Eq. 1 does not capture the special case that all z_{si} are zero, that is, sBS *s* does not provide any traffic to any MT (this actually corresponds to a trivial case that no traffic offloading occurs at sBS *s*). Parameter n_{si} denotes the power of the background noise. To capture the influence of the intermittent EH supply, we introduce

$$P_{out} = \left(p_{si} r_{si}, \{z_{si}\}_{i\in\mathcal{I}}\right) = \mathbf{Pr}\left\{ r_{si} \geq W_s \log_2\left(1+\frac{\left(p_{si}\sum_{i\in\mathcal{I}} z_{si}+Q_s)g_{si}\right)}{n_{si}\sum_{i\in\mathcal{I}} z_{si}}\right)\right\} \qquad (2)$$

to denote the outage probability that sBS *s*'s achievable offloading rate x_{si} cannot meet the assigned rate r_{si}.

We consider the following optimization problem to exploit the EH supply.

(Objective) We aim at minimizing the total on-grid power consumption of all macro and small cells.

(Constraints) We take into account the sBS-MT selection constraint, the MT's QoS constraint, and the mBS's and sBSs' power capacity constraints. Specifically, in DC-enabled offloading, each MT can only select one sBS to provide traffic, and each sBS, due to the limited resource blocks, can select no more than a given number of MTs to serve. In addition, each MT is guaranteed to receive a total successful data rate equal to its requirement R_i^{req}, that is, $\sum_{s\in\mathcal{S}} z_{si} (x_{Bi(s)} + r_{si} (1 - P_{out}(p_{si}, r_{si}, \{z_{si}\}_{i\in\mathcal{I}})) = R_i^{req}$, where $x_{Bi(s)}$ is the data rate provided by the mBS.

(Control Variables) We jointly optimize the sBS-MT association, the offloading rate scheduling between the macro and small cells, and the

With ES, a group of neighboring small/macro cells can form a local energy network in which they can cooperatively share the locally stored energy (e.g., the harvested green energy) to improve the overall energy utilization. However, how to realize the local energy-sharing network has imposed a challenge.

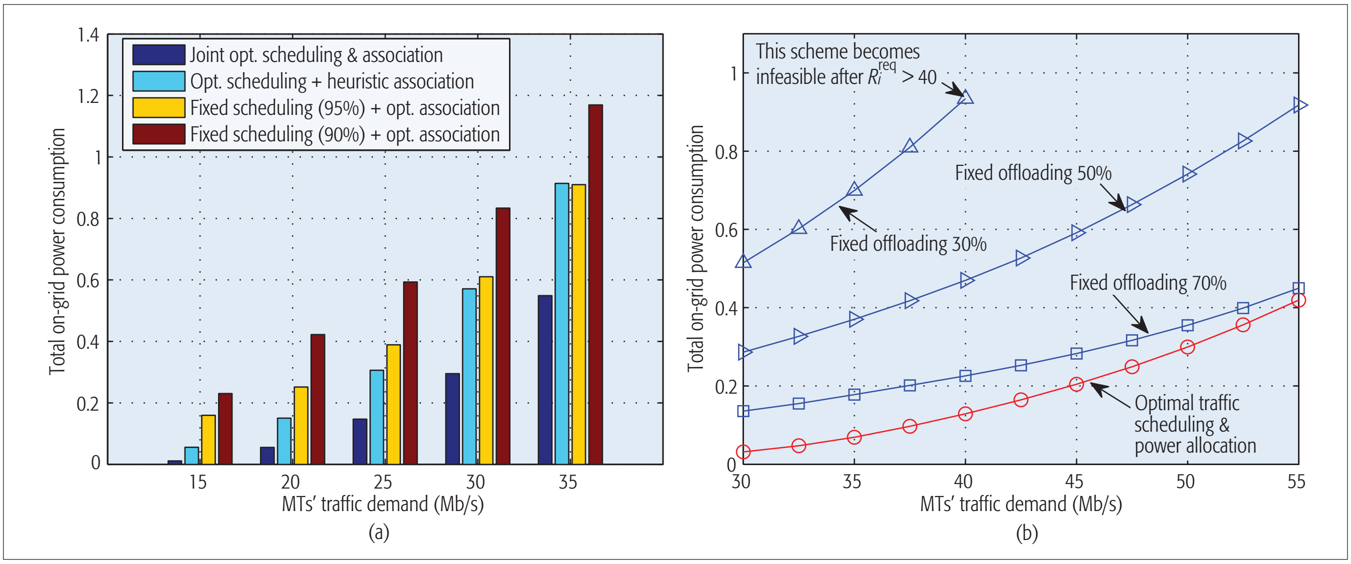

Figure 5. Performance of proposed offloading scheme: a) advantage of optimal offloading scheme in saving the total on-grid power consumption; b) advantage of optimal offloading scheme in saving total on-grid power consumption from the perspective of an individual sBS-MT pair.

corresponding transmit-powers of the macro and small cells.[2]

We evaluate the advantage of the proposed DC-enabled offloading via numerical tests. The detailed parameter settings are as follows. The mBS is located at the origin (0 m, 0 m), and three sBSs are located at (250 m, 0 m), (220 m, 30 m), and (250 m, –30 m). The group of MTs are randomly located within a plane whose center is (220 m, 0 m) and radius is 20 m; that is, the MTs are geographically closer to the sBSs than the mBS, which is a favorable condition for offloading traffic. We set all channel power gains according to the path loss model, the maximum on-grid transmit power of mBS for each MT as 1 W, and the maximum on-grid transmit-power of an sBS for each MT as 0.4 W. The mBS's channel bandwidth is 10 MHz, each sBS's channel bandwidth is 5 MHz, and the density of the background noise is 10^{-14} W.

Figure 5a shows the advantage of the optimal offloading (i.e., the optimal joint sBS-MT association, traffic scheduling, and power allocation) in reducing the total on-grid power consumption. For the purpose of comparison, we consider two other heuristic schemes, namely, the combination of the optimal traffic scheduling and power allocation for each individual sBS-MT pair but heuristic sBS-MT association (i.e., each MT myopically chooses the nearest sBS to offload data), and the combination of the optimal sBS-MT association but heuristic traffic scheduling (i.e., each MT offloads a fixed ratio of its traffic demand through the associated sBS, and we use two fixed ratios of 90 and 95 percent as examples). Figure 5a shows that the optimal offloading scheme can significantly outperform the other schemes (i.e., consuming much less total on-grid power compared to the other schemes). The results validate the significant benefits from optimally exploiting the sBSs' EH supply and the DC feature in traffic offloading.

Figure 5b further shows the advantage of the optimal traffic scheduling and power allocation from the perspective of an individual sBS-MT pair. As shown in Fig. 5b, using the optimal traffic scheduling and the associated power allocation can significantly reduce the total on-grid power consumption, in comparison with using the fixed offloading ratio (i.e., the MT always offloads a fixed portion of the traffic demand to the sBS). Such an advantage essentially stems from the fact that the optimal scheme properly controls the offloading rate to the sBS to avoid too much offloading outage (due to the intermittency of the sBS's harvested energy), which thus effectively helps save the total on-grid power usage.

RESEARCH DIRECTIONS

We discuss two important research directions about the green-oriented traffic offloading as follows.

ENHANCED PHY/MAC TECHNOLOGIES

The recent NOMA, massive multiple-input multiple-output (MIMO), and full-duplex in the physical/medium access control (PHY/MAC) layer provide promising approaches to improve spectrum efficiency and accommodate massive connections in traffic offloading. It is an interesting future direction in green-oriented design of traffic offloading that integrates NOMA/massive MIMO/full-duplex and exploits the advanced energy technologies (i.e., EH, ES, and WPT) to simultaneously improve energy efficiency and spectrum efficiency. For instance, NOMA provides an efficient and promising multiple access scheme to enhance the traffic offloading via small cells (especially with the DC). However, the nature of NOMA yields co-channel interference among different users or cells reusing the same frequency channel, which results in the performance of NOMA being sensitive to the limited energy supply. Such a phenomenon will become even more aggravated when exploiting EH/ES in energy supply for traffic offloading.

COMPUTATION OFFLOADING VIA MOBILE CLOUD

With the growing popularity of mobile cloud applications and mobile edge computing, mobile devices are able to intelligently offload com-

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[2] The optimization problem can be solved by exploiting the layered structure property. We skip the details in this article due to limited space.

putational tasks to mobile cloud platforms for obtaining powerful computational and storage resources. Such a computation offloading involves a joint design of traffic offloading (when delivering the massive data to/from the cloud infrastructure) and resource allocation for executing computational tasks at the cloud infrastructure. Hence, it is interesting to investigate green-oriented computation offloading through mobile cloud, which is powered by the advanced energy technologies such as EH and ES.

The nature of NOMA yields co-channel interference among different users or cells reusing the same frequency channel, which results in that the performance of NOMA is sensitive to the limited energy supply. Such a phenomenon will become even more aggravated when exploiting EH/ES in energy supply for traffic offloading.

Conclusion

In this article, we have presented the architecture of green-oriented traffic offloading in HCNs that exploits advanced energy technologies including EH, ES, and WPT. The challenges in exploiting EH, ES, and WPT to support traffic offloading have been discussed, and the possible solutions have been discussed, especially by exploiting the paradigm of small cell DC in recent 3GPP specifications. We have also presented a case study on DC-enabled traffic offloading through EH-powered small cells, with the objective of minimizing the total on-grid power consumption of all macro and small cells. Finally, we have shared some research directions in green-oriented traffic offloading in HCNs.

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