Energy-Sustainable Traffic Steering for 5G Mobile Networks

Shan Zhang, Ning Zhang, Sheng Zhou, Jie Gong, Zhisheng Niu, and Xuemin (Sherman) Shen

The authors propose an energy-sustainable traffic steering framework, where the traffic load is dynamically adjusted to match with energy distributions in both the spatial and temporal domains by means of inter- and intra-tier steering, caching, and pushing.

ABSTRACT

Renewable EH technology is expected to be pervasively utilized in 5G mobile networks to support sustainable network developments and operations. However, the renewable energy supply is inherently random and intermittent, which could lead to energy outage, energy overflow, QoS degradation, and so on. Accordingly, how to enhance renewable energy sustainability is a critical issue for green networking. To this end, an energy-sustainable traffic steering framework is proposed in this article, where the traffic load is dynamically adjusted to match energy distributions in both the spatial and temporal domains by means of inter- and intra-tier steering, caching, and pushing. Case studies are carried out, which demonstrate that the proposed framework can reduce on-grid energy demand while satisfying QoS requirements. Research topics and challenges of energy-sustainable traffic steering are also discussed.

INTRODUCTION

The fifth generation (5G) mobile networks are expected to connect trillions of devices and provide 1000-fold network capacity by 2020 compared to that in 2010. Network densification (i.e., deploying more small cell base stations [SBSs]) can effectively improve the network capacity through spectrum reuse, and thus is considered as the key cornerstone for 5G. However, network densification may lead to huge energy consumption, causing heavy burdens on network operators. To tackle the cumbersome energy consumption, energy harvesting (EH) technology can be leveraged. Particularly, EH enabled base stations (EH-BSs) can exploit renewable energy as supplementary or alternative power sources to reduce operational expenditures (OPEX). In addition, EH-BSs can be deployed more flexibly without the constraint of power lines. By 2011, over 10,000 EH-BSs were deployed globally, and this figure will increase to more than 400,000 by 2020 [1].

Despite the potential advantages, the inherent randomness of renewable energy poses significant technical challenges to network operations. Specifically, the mismatch between harvested energy and traffic distributions may result in energy outage and/or energy overflow, degrading the quality of service (QoS) and energy utilization. Thus, in addition to energy efficiency, a new performance measure, "energy sustainability," should be introduced to keep the energy outage and energy overflow probabilities as low as possible [2]. To this end, we propose a traffic steering framework to enhance energy sustainability in networks with EH-BSs.

Traffic steering goes beyond traffic offloading, which proactively adjusts traffic distribution to match with and better utilize network resources, aiming to enhance network performance or providing better QoS [3].

The proposed framework encompasses three approaches: inter-tier steering, intra-tier steering, and content caching and pushing. Specifically, inter-tier steering adjusts the traffic load of each tier according to the variation of renewable energy arrival rate in a large timescale. In addition, intra-tier steering shifts traffic among neighboring BSs to further break down traffic load in the spatial domain, while content caching and pushing reshape temporal traffic load to overcome small timescale randomness, based on the instant energy status. Together, these three approaches can match traffic demand to renewable energy supply in both the spatial and temporal domains, reducing the probabilities of energy outage and overflow. Therefore, the proposed framework provides two-fold benefits of greenness and QoS provisioning, achieving energy-sustainable networking.

The remainder of this article is organized as follows. An overview of 5G networks with EH is first presented in the following section. Then the energy-sustainable traffic steering framework is introduced, including detailed methods, research topics, and challenges. Case studies are conducted to reveal the effectiveness of energy-sustainable traffic steering, followed by the conclusions.

HETEROGENEOUS NETWORKS WITH ENERGY HARVESTING

In this section, we introduce EH-enabled networks, including architecture, challenges, existing solutions, and limitations.

EH-ENABLED 5G NETWORK ARCHITECTURE

With the promising EH technologies leveraged, the resulting 5G network architecture is shown in Fig. 1. Particularly, SBSs can be further classified into three types based on the functions and power sources:

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- Off-grid EH-SBSs, powered solely by renewable energy without access to power grid
- On-grid EH-SBSs, powered jointly by power grid and renewable energy
- Conventional SBSs, powered only by power grid

Notice that the three types of SBSs have distinct features. Off-grid EH-SBSs enable the most flexible deployment, whereas the QoS cannot be guaranteed well due to the unstable energy supply. Thus, off-grid EH-SBSs can be deployed for opportunistic traffic offloading for macro BSs (MBSs). On-grid EH-SBSs provide reliable services with on-grid power as backup sources, which can also use the renewable energy to reduce the OPEX. However, they bring the highest capital expenditure due to the EH modules and wired connections to power grid. Conventional SBSs are the moderate option, which guarantee QoS requirements but with the highest on-grid power consumption.

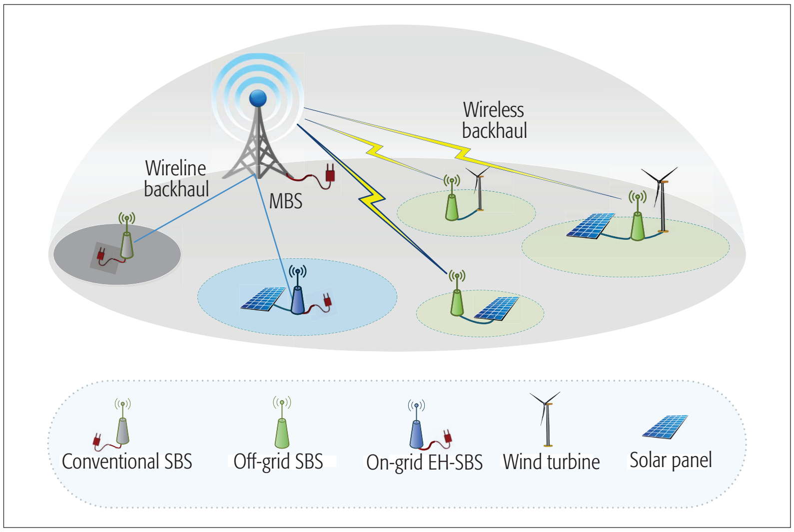

Figure 1. Network architecture with renewable energy harvesting.

Mismatched Traffic and Energy

As the cellular systems are expected to provide reliable services with guaranteed QoS, the power supply and demand of each BS should be balanced. For conventional BSs, the on-grid power supply can be dynamically adjusted based on the traffic variations. However, it is much more challenging for EH-BSs, as the renewable energy arrival is usually mismatched with the traffic demand. For example, the two-day traffic and renewable energy variations are shown in Fig. 2, wherein the traffic profile is obtained from real data measurement in the EARTH project [4], and the renewable power profile is collected by the Elia group [5]. The mismatch of renewable energy and traffic load variations may bring following problems.

Renewable Energy Outage: This happens when the energy arrival rate is lower than the BS power demand, which may cause additional on-grid power consumption or degrade QoS. For example, off-grid EH-BSs even have to be shut down when the renewable energy is insufficient to support their static power need [4]. Although multiplexing diverse renewable energy sources helps to improve the reliability, the randomness still exists, and energy outage cannot be avoided.

Renewable Energy Overflow: This occurs when the renewable energy is oversupplied compared to the traffic demand. To address this problem, batteries can be used to store the redundant energy for future use. However, in practical systems, the battery capacity is usually limited due to high cost, and energy overflow is still inevitable.

Spatial Supply-Demand Imbalance: This is due to the diverse energy sources of different BSs. Furthermore, renewable energy is non-uniformly distributed in the spatial domain, which may be mismatched with the traffic load in that domain. Thus, neighboring BSs can have imbalanced renewable energy supply across the network, leading to inefficient network-wide renewable energy utilization.

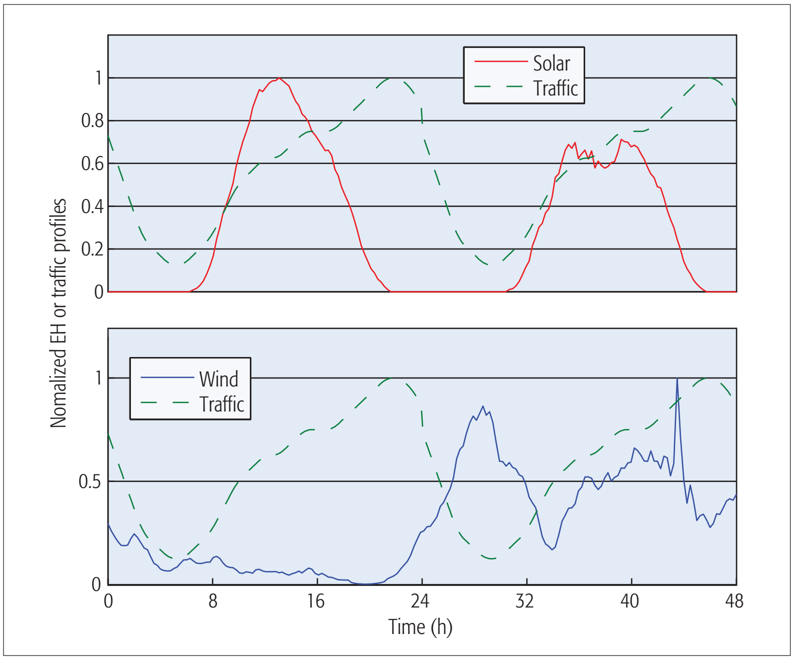

Figure 2. Daily energy harvesting and traffic demand profiles.

Energy-Sustainable Networking

The challenges of renewable energy dictate that the network design criterion should shift from minimizing the total energy consumption toward energy sustainability, that is, to sustain traffic while satisfying the QoS requirements with energy dynamics. Specifically, energy-sustainable networking improves the utilization of renewable energy to mitigate energy outage and overflow, which enables better QoS provisioning and reduces on-grid power demand. To achieve this goal, the energy supply and the traffic demand should be matched with each other in both the spatial and temporal domains [6].

Existing research mostly focuses on the energy management perspective, which reshapes energy supply to match the given traffic distribution. The methods can be mainly classified into two categories.

BS-Level Energy Allocation: Through dynamic charging and discharging, the renewable energy can be reallocated in the temporal domain to match the time-varying traffic load. For example, effective online and offline energy scheduling schemes have been proposed to minimize the

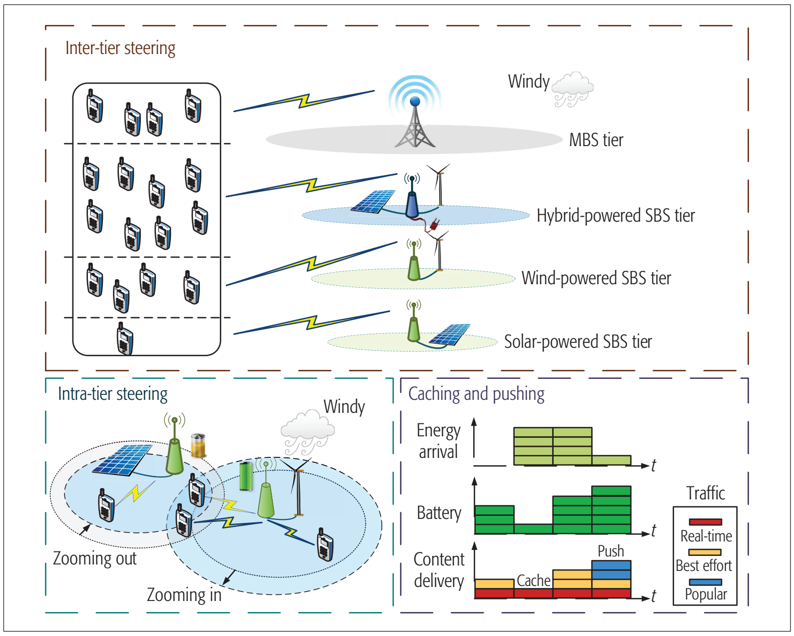

Figure 3. Energy-sustainable traffic steering framework.

on-grid power consumption of a single EH-BS, assuming infinite battery capacity [7]. However, in real systems, the performance of these methods may be degraded due to battery limitations.

Network-Level Energy Cooperation: Through energy transfer among EH-BSs, renewable energy can be redistributed across the network to match the traffic load, which can further reduce renewable energy waste [8]. However, the EH-BSs need to be connected through either dedicated power lines or smart grids to implement this approach [9]. Besides, the two-way power transmission among EH-BSs may cause the loss of renewable energy.

Notice that the existing methods of energy management manifest their limitations in terms of performance and prerequisite power infrastructure; hence, we seek solutions from the traffic steering perspective, which is more flexible and can easily be realized through control signaling without any additional deployment of power infrastructures. Our previous work was the first to adopt EH-SBS traffic offloading to tackle renewable energy dynamics [10]. In this article, we propose a comprehensive traffic steering framework, where traffic is manipulated dynamically in different spatial and temporal scales to match the renewable energy supply.

Energy-Sustainable Traffic Steering

In this section, we first introduce the concept and applications of traffic steering, and then propose an energy-sustainable traffic steering framework to realize traffic-energy matching in heterogenerous networks (HetNets) with EH.

Traffic Steering Concept

The heterogeneous 5G networks call for sufficient utilization of available resources to support the dynamic and differentiated traffic demand. However, the conventional user association method is mainly based on received signal-to-interference-plus-noise ratio (SINR), which can fail to meet this requirement. To deal with this challenge, traffic steering redistributes traffic load across the network based on radio resources to optimize the performance of networks and end users. As user association goes beyond "SINR-based" to "resource-aware," traffic steering can effectively enhance network utility through appropriate traffic-resource matching.

The objectives and policies of traffic steering can be diverse. For example, traffic can be steered from heavily loaded cells to lightly loaded ones for load balancing, aiming to maximize network capacity. Besides, in networks with multiple radio access technologies (RATs), users can be steered to different RATs according to their mobility, such that call dropping probability can be reduced. In addition, traffic steering can also be performed in the temporal domain through transmission scheduling and rate control. For instance, the transmission of best effort traffic can be postponed (i.e., steered to future time slots) when the traffic demand exceeds network capacity.

Traffic Steering with EH

With EH leveraged, the key challenge is that the service capability of a BS can vary dynamically with renewable energy supply, which requires the traffic load to be matched with the corresponding service capability to fully utilize renewable energy. To this end, we propose an energy-sustainable traffic steering framework that encompasses three main approaches, as shown in Fig. 3. Inter-tier steering optimizes the amount of traffic steered to different tiers over a large timescale, based on the statistic information of renewable energy supply. Then intra-tier steering, caching, and pushing dynamically reshape traffic load on smaller scales to achieve fine-grained traffic-energy matching. Specifically, intra-tier steering adjusts the BS-level traffic load to the corresponding energy supply through cooperation among multiple neighboring cells. Meanwhile, caching and pushing schedule content delivery by exploiting the content information and differentiated QoS requirements, which can be conducted independently at each BS to further deal with the small timescale randomness of energy and traffic dynamics.

Inter-Tier Steering: As shown in Fig. 1, BSs can be further divided into multiple tiers based on power sources, cell type, and other system parameters. Each tier has different service capabilities, which can vary dynamically with renewable energy arrival rate. Energy-sustainable inter-tier traffic steering dynamically optimizes the amount of traffic steered to each network tier, based on the information of energy supply and other system parameters. Intuitively, more traffic can be steered to the EH-SBS tiers with sufficient energy for service, which reduces the on-grid power consumption of other tiers. On the contrary, EH-SBSs with insufficient energy supply can reduce transmit power consumption by serving fewer users to maintain the power balance (e.g., solar-powered SBSs on a cloudy day). In addition, EH-SBSs can be deactivated when the power supply is even lower (e.g., solar-powered SBSs at midnight), which can further save the static power consumption (e.g., air conditioning) to enhance renewable energy sustainability.

With intelligent inter-tier traffic steering, the traffic load can be reshaped in both the spatial and temporal domains simultaneously. In the spatial domain, the traffic load of each tier is optimized based on their service capability, as shown in Fig. 3. From the whole network perspective, the traffic load supported by different energy sources is also dynamically adjusted with on-grid BSs serving as backups, which in fact realize temporal traffic-energy matching.

Intra-Tier Steering: Intra-tier traffic steering further adjusts BS-level traffic load through methods of cell zooming and BS cooperation, which further break up traffic load in the spatial domain based on energy status. With cell zooming, the coverage of a BS can be enlarged (i.e., zoom in) or shrunk (i.e., zoom out) to adjust the corresponding traffic load through transmit power control and antenna tilting. In conventional on-grid networks, traffic is generally steered from heavily loaded cells to lightly loaded ones, leading to load-dependent cell size. With EH technology implemented, EH-BSs should further adjust cell size based on the corresponding energy supply. For example, the EH-BSs with oversupplied energy can zoom in to assist the transmission of neighboring BSs by utilizing the redundant harvested energy. In reward, some EH-BSs encountering energy shortage can shrink their coverage to reduce their traffic load (i.e., zooming out). By doing so, traffic is steered to EH-SBSs with redundant renewable energy, reducing service outage and battery overflow.

In addition to cell zooming, energy-aware cooperative transmission can also be applied. As networks become ultra dense, a mobile user may be covered and served by multiple BSs simultaneously. In this case, the cooperative transmission of these BSs can be optimized based on their energy status in addition to channel condition. For instance, BSs with insufficient renewable energy or large path loss can reduce transmit power or even turn off, while others enlarge transmit power to guarantee QoS.

Caching and Pushing: Caching and pushing aim to schedule content delivery in an optimal manner by exploiting the information of contents, user preference, and differentiated QoS requirements, which can reshape traffic load to deal with the small timescale randomness of renewable energy arrival.

The transmission of non-real-time traffic can be postponed during energy shortage periods by caching corresponding contents at a BS. For example, the packet can be delivered with lower transmission rate to reduce energy consumption as long as the given deadline is satisfied, while the transmission of best effort traffic can be delayed until the energy is sufficient. The main idea of proactive pushing is that the EH-BSs can deliver the popular contents (e.g., videos and news) in a multicast manner before user request, when the energy is sufficient or oversupplied. By storing the contents at end-user devices, the amount of data transmission can be reduced. In fact, the demand of video streaming, currently accounting for over 50 percent of wireless traffic and still increasing, is expected to dominant mobile data service. Surprisingly, 10 percent of the most popular videos receive nearly 80 percent of views. Therefore, proactive pushing can effectively reduce the future traffic load.

Through energy-sustainable caching and pushing, the traffic load is equivalently steered from periods of energy shortage to periods of energy oversupply. This traffic reshaping enables traffic-energy matching in smaller timescales, further enhancing energy utilization.

Research Challenges

Based on the design scales, inter-tier steering, intra-tier steering, caching, and pushing can be conducted at the hour, minute, and second levels, respectively, providing both coarse- and fine-grained network optimization. As such, energy-sustainable traffic steering can match traffic demand to energy supply flexibly in the spatial and temporal domains, providing two-fold benefits of greenness and QoS. To realize the potential advantages, several research challenges to implement energy-sustainable traffic steering are discussed as follows.

Service Capability with EH: Since traffic steering is done mainly to match the traffic load to the corresponding service capability from different spatial-temporal scales, a fundamental problem is to analyze the EH-enabled service capability of each BS and network tier. In the existing literature, the link-level channel capacity has been extensively studied, with an EH-enabled transmitter and a single or multiple receivers [11]. However, network-level analysis can be much more challenging due to factors such as random traffic distribution, user mobility, differentiated QoS requirements, inter-cell interference, and HetNet architecture. Stochastic geometry can be applied to QoS analysis of large-scale networks, based on the information of traffic distribution and network topologies. For conventional on-grid HetNets, network capacity has been investigated with respect to different QoS performance metrics, such as coverage probability and user achievable rate. Future work should revisit these issues considering the influence of renewable energy supply in both large and small timescales [12].

Low-Complexity Operation: Traffic steering in the spatial domain needs the cooperation of multiple cells from the same or different tiers, where the BS activation/deactivation, power control, and user association should be jointly optimized based on the instant information of traffic distribution and renewable energy supply. The problem is to minimize the long-term on-grid energy consumption subject to QoS requirements and power constraints, which can be formulated as a mixed-integer programming problem. The existing literature mainly focus on traffic steering optimization for small-scale networks, whereas the operational complexity can increase exponentially with network scale due to the coupled operation of different cells [13]. As future mobile networks are expected to be ultra-densely deployed with massive device connections, low-complexity steering schemes are critical for practical implementation. To this end, the BS operations can be decoupled in both the temporal and spatial domains. In the temporal domain, the deactivation of BSs can be determined over a large timescale based on the statistic information of energy and traffic arrivals, and then each active BS can further schedule the content delivery over a small timescale based on the instant states. In the spatial domain, the con-

Caching and pushing aim to schedule content delivery in an optimal manner by exploiting the information of contents, user preference, and differentiated QoS requirements, which can reshape traffic load to deal with the small timescale randomness of renewable energy arrival.

Existing studies have designed spatial traffic steering schemes based on a semi-static traffic model, and also proposed dynamic content caching and pushing schemes from a single BS perspective. The joint optimization of spatial and temporal traffic steering offers opportunities to further improve network performance.

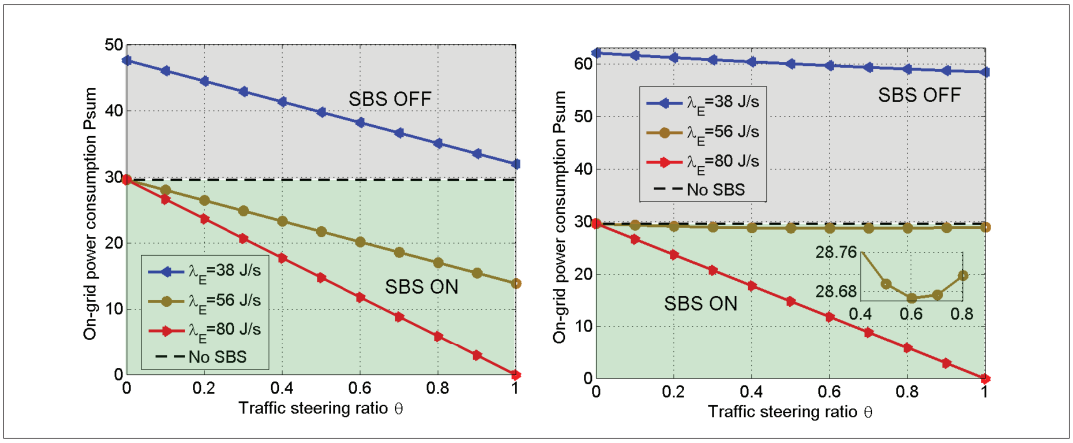

Figure 4. Power consumption with respect to traffic steering ratio: a) on-grid EH-SBS; b) off-grid EH-SBS.

cept of self-organized networking (SON) can be applied to design effective distributed traffic steering schemes, such that BSs can make decisions independently with local information [14].}}

Joint Spatial-Temporal Optimization: Existing studies have designed spatial traffic steering schemes based on a semi-static traffic model [10], and also proposed dynamic content caching and pushing schemes from a single BS perspective. The joint optimization of spatial and temporal traffic steering offers opportunities to further improve network performance. In this case, mobile operators have a higher degree of freedom to reshape traffic load. For instance, the oversupplied energy at a BS can be utilized for:

1. Zooming in to assist neighboring cells
2. Serving more traffic from upper-tier on-grid MBSs
3. Pushing popular contents to users proactively
4. Storing the redundant energy in battery for future use

The Markov decision process (MDP) method can be applied to design optimal steering policies through theoretical analysis of small-scale networks, which can provide a guideline to practical network operation. Furthermore, advanced machine learning technologies can be implemented to devise a spatial-temporal traffic steering method for large-scale networks based on the big data analysis in real systems [15, 16].

Trade-off between System and User Performance: Although traffic steering helps to improve network performance, the interests of end-user devices may be degraded. Some end devices may not be connected with the preferred BS after being steered in the spatial domain, and therefore they have to increase the transmit power to maintain the uplink QoS. Accordingly, the batteries of end devices may be consumed quickly. Moreover, for temporal traffic steering, proactive pushing and caching also consume the resources of end devices, which may be unacceptable from the perspective of mobile users. Existing traffic steering mainly focuses on the performance optimization from the network perspective, while the trade-off between network and user profits has not been well studied. For practical implementation, incentive schemes need to be designed to compensate the performance degradation of steered users, whereby the agreement can be achieved between network operators and mobile users. Such problems can be modeled as two-player or multi-player games, and game theory can be applied to seek equilibria among players.

Case Study: Inter-Tier Steering

In this section, a case study is carried out on inter-tier steering to illustrate practical implementation in detais. We consider a two-tier HetNet consisting of a conventional MBS with radius 1000 m and multiple EH-SBSs with coverage radius 100 m. The available bandwidths for the MBS and SBS are set as 10 MHz and 2 MHz, respectively. The traffic distribution is modeled as a Poisson point process (PPP) with density 1500 /km^2, and the average rate per user should be no smaller than 500 kb/s. Traffic within each small cell can be partially or completely steered from the MBS to the EH-SBS depending on the renewable energy arrival rate. Specifically, we analyze how much traffic should be steered to match the EH-dependent service capability, from the perspective of a typical EH-SBS. Define by θ the steering ratio, that is, the percentage of traffic steered to the EH-SBS within the small cell. For the given renewable energy arrival rate, we demonstrate the on-grid power consumption variation with respect to θ to investigate the influence of energy supply on the BS-level service capability and the optimal traffic steering volume.

Consider the discrete power consumption model, with per unit energy set as 1 J. The energy arrival at an EH-SBS is modeled as Poisson process with rate λ_E for tractable analysis, which is saved at the battery for future use. Both on-grid and off-grid EH-SBSs are considered, which are assumed be to 500 m away from the MBS. For the on-grid EH-SBS, it can consume either renewable or on-grid power, but the on-grid power can only be used as backup when the battery is empty. The off-grid EH-SBS has to shut down when the battery becomes empty, and meanwhile, all traffic is steered to the MBS through a handover procedure, causing additional handover cost. The BS power consumption model is based on the EARTH project [4], and power control can be conducted by partially deactivating the subframes. For the wireless channel model, the path loss exponent, noise, and interference densities are set as 3.5, –105, and –100 dBm/MHz, respectively. Denote by P_{sum} the on-grid power required to serve the traffic located within the coverage of a small cell. Under different energy arrival rate λ_E, the relationship between P_{sum} and the steering ratio θ is shown in Fig. 4, with the handover cost set as 1.5 J. For comparison, the dashed lines show the power consumption if the EH-SBS is not deployed and all traffic is served by the MBS. Therefore, activating an EH-SBS for traffic steering even increases power consumption in the regions above the dashed lines, and thus the EH-SBSs should be completely deactivated.

The on-grid power consumption P_{sum} is shown to decrease with θ when the on-grid EH-SBS is active, indicating that the active on-grid EH-SBS should serve traffic as much as possible. Furthermore, P_{sum} decreases with λ_E, as more renewable energy can be utilized. However, steering traffic to the on-grid EH-SBS does not always save energy, even under the optimal steering ratio. For example, the minimal on-grid power consumption is around 32 W when λ_E = 38 J/s (with θ = 1), while only 30 W is needed if the EH-SBS is not activated, shown as the dashed lines in Fig. 4a. The reason is due to the trade-off between transmission and static power consumption. On one hand, steering traffic to the SBS helps to reduce transmission power, as the SBS provides higher spectrum efficiency due to the short transmission path. On the other hand, the active SBS also requires static power independent of data transmission [4], which may increase the total on-grid power consumption when renewable energy is insufficient. This trade-off is influenced by the renewable energy arrival rate, which directly determines the network power consumption. Therefore, the on-grid EH-SBSs should be turned off under low energy arrival rate, whereas they should try to serve as much traffic as possible once activated.

As for the off-grid EH-SBS, the optimal ON-OFF states also depend on the renewable energy arrival rate. However, the optimal traffic steering ratio may not be 1. As an example, the energy-optimal steering ratio is 0.6 when the renewable energy arrival rate is 56 W. This is due to the trade-off between the handover cost and the power saved at the MBS. With more traffic steered to EH-SBSs, the power consumption of the MBS is reduced, whereas the renewable energy of the EH-SBSs can be used up more quickly if insufficient, leading to frequent user handover and extra cost. This trade-off determines the optimal steering ratio and ON-OFF status of the off-grid EH-SBS, based on the renewable energy arrival rate. Furthermore, the optimal steering ratio indicates the service capability of EH-SBSs, which increases with renewable energy arrival rate. When the energy arrival rate is high (e.g., λ_E = 80 J/s), the EH-SBS should serve all traffic within coverage (i.e., θ = 1), reflecting high service capability. On the contrary, the EH-SBS should be deactivated and serve no traffic (i.e., θ = 0) under low energy arrival rate (e.g., λ_E = 38 J/s), reflecting zero service capability.

To evaluate the effectiveness of energy-sustainable traffic steering, we illustrate the daily power consumption profiles of an on-grid EH-SBS under different traffic steering schemes. The traffic and solar energy profiles shown in Fig. 2 (the first day) are adopted, with the peak energy arrival rate and traffic load set as 100 λ_E/s and 3000 θ/km^2, respectively. The greedy algorithm keeps the EH-SBS on to serve all the traffic within coverage. The proposed energy-sustainable scheme dynamically adjusts the ON/OFF states and the traffic load of the EH-SBSs to minimize the on-grid power consumption, based on the results of Fig. 4. The temporal variations of on-grid power consumption under the two schemes are demonstrated in Fig. 5. Specifically, it is shown that the proposed energy-sustainable traffic steering scheme can reduce the on-grid power consumption by 48 percent on average, compared to the greedy scheme. Furthermore, the proposed algorithm is more effective during low energy hours.

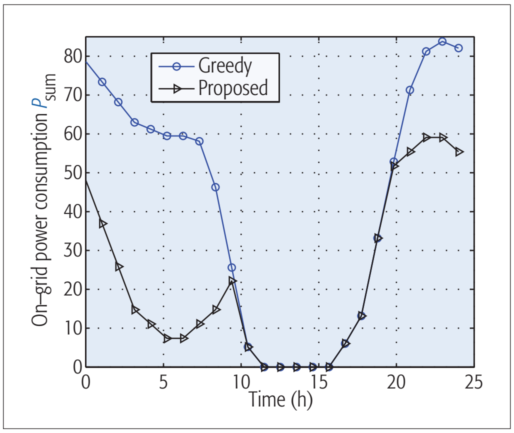

Figure 5. Daily on-grid power consumption under different traffic steering schemes.

Although traffic steering helps to improve network performance, the interests of end user devices may be degraded. Some end devices may not be connected with the preferred BS after steered in spatial domain, and thereby they have to increase the transmit power to maintain the uplink QoS. Accordingly, the battery of end devices may be quickly consumed.

Conclusions

In this article, an energy-sustainable traffic steering framework has been proposed to address the sustainability issue of 5G networks by encompassing three approaches:
- Inter-tier steering
- Intra-tier steering
- Content caching and pushing

The proposed framework can better balance the power demand and supply of individual EH-BSs by matching the traffic load and renewable energy distribution in both the spatial and temporal domains. The case study on inter-tier offloading has demonstrated that the ON-OFF status and the steered traffic load of each EH-SBS should be adapted to the corresponding energy-dependent service capability, such that the on-grid power consumption can be effectively reduced. Future research topics and challenges are also discussed.

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