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Energy Sharing within EH-Enabled Wireless Communication Networks

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***Abstract*—As energy harvesting (EH) technologies advance, wireless networks will potentially and eminently be powered by the harvested energy such that carbon footprints can be reduced. Challenged by the dynamic nature of the green energy source availability, various methods have been proposed so that the harvested energy can be hoarded for future use or transferred to other devices, such as the storage unit of individual EH devices and energy sharing policy among multiple EH devices within the network. This article provides an overview on the architecture of EH enabled base stations and discusses two energy sharing mechanisms within the wireless communication network: direct energy transfer based schemes (through either wired power grid or wireless energy transfer), and non-direct energy transfer based schemes (traffic offloading and cooperative transmission). We compare the energy sharing schemes and lay out basic design principles and research challenges on optimizing energy harvesting enabled wireless networks.**

***Index Terms*—Energy harvesting (EH), energy sharing, direct energy transfer, non-direct energy transfer.**

I. INTRODUCTION

Energy harvesting refers to the concept of taking fuel from readily available ambient sources that are free for users, including wind, solar, biomass, hydro, geothermal, tides, and even radio frequency signals [1]. As compared with both battery powered and main grid powered wireless nodes, which rely on **non-renewable brown energy**, energy harvesting devices (EHDs) can preclude energy related inhibition as long as the **renewable green energy** source is ample and stable in the sense of availability.

Various green energy sources of *passively powered devices* (that do not require any internal power source and sometimes use different green energy sources) and *hybrid powered devices* (that have a backup non-renewable energy source in case the power provided by energy harvesting is insufficient) are introduced in [2]. Since the *energy-arrival rate* is determined by the surrounding environment of EHDs, such as geo-locations and weather conditions, existing literature primarily focuses on overcoming the dynamics of the green energy sources and ensuring long-term, uninterrupted operation.

For each energy harvesting device, the *energy causality constraint* (EC-constraint) imposes that the total consumed energy cannot exceed the total harvested energy, and the *energy half-duplex constraint* (EH-constraint) mandates that energy harvested by each EHD in the current time slot can only be used in subsequent time slots. With these energy related constraints, realistic challenges such as limited battery capacity, leakage of energy storage devices, as well as the device complexity, have to be delineated for the large scale implementation of energy harvesting devices.

Since renewable energy powered wireless networks are prevailing in the foreseeable future, this article provides an overview of energy harvesting base stations and energy management schemes for practical scenarios, where instantaneous energy arrival rates may not be readily and practically obtained. In particular, instead of keep pushing the energy storage capacity of individual green energy enabled base stations, *energy sharing techniques* are explored such that multiple devices can act as the remote battery storage for each other, and the energy availability of each node within the network can be controlled.

Intuitively, energy sharing requires energy to be transferred directly from one device to another. Based on the medium that is used to transfer energy, *direct energy transfer based energy sharing* can be classified into two categories: *wired energy sharing* that relies on the pre-installed power grid within the wireless network architecture, and *wireless energy sharing* that facilitates energy transfer among devices in the form of radio frequency (RF) signals, i.e., RF energy harvesting.

In addition to the direct energy transfer based energy sharing techniques, the broadcasting nature of wireless signals can be utilized such that energy can be shared within the network without physically transferring energy from one place to another. *Non-direct energy transfer based energy sharing* mainly relies on *traffic offloading* and *cooperative transmission* techniques, which can leverage energy dynamics among multiple devices within the network.

To further facilitate EH enabled wireless networks and mitigate the above mentioned EC/EH constraints, the comparison of various energy sharing schemes are conducted with the consideration of the versatile and flexible network architectures, including the readily deployed low power small cell tier and device to device (D2D) communication tier.

II. ENERGY HARVESTING ENABLED WIRELESS COMMUNICATION NETWORKS

Energy harvesting is empowering a new paradigm of wireless communication networks (WCNs). Individual base stations (BSs) in macro cells or small cells are now capable of becoming energy providers. As illustrated in Fig. 1, either being connected to the green power farm through the power grid or having standalone green power generators, EH enabled macro BSs and low power nodes (LPNs) are readily constructed by telecommunications equipment manufacturers [1].

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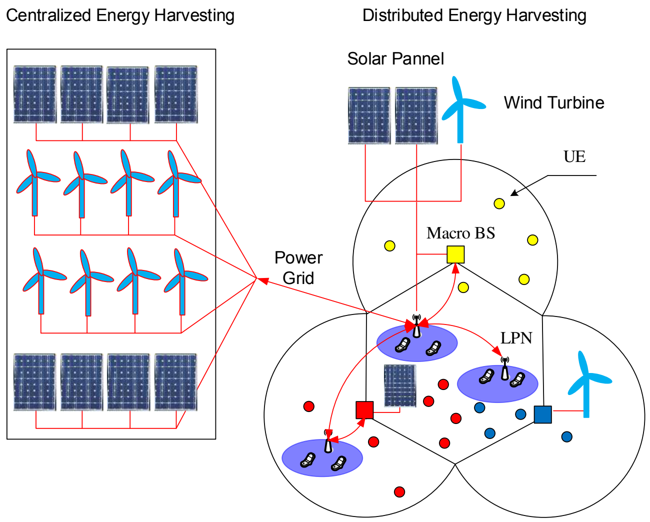


Fig. 1. Energy harvesting enabled wireless communication networks.

Although EH enabled base stations (EH-BSs) can be run by either centrally or distributively harvested green energy, depending on the mechanisms in coping with the dynamics of energy related constraints, EH-BSs can be classified into four categories as shown in Table III. Type I EH-BS can only rely on the instantaneous harvested energy provided by its own energy harvesters; Type II can last longer by leveraging the energy stored in the battery, and eventually goes to sleep when the storage energy is exhausted. Type III EH-BS can utilize the instantaneous energy harvested by its own energy harvesters as well as the harvested energy provided by the power grid. Type IV is the most reliable EH-BS in terms of green energy availability as it is equipped with distributed power generator and the grid is connected with the green power plant as well. Note that in addition to the harvested green energy, the grid architecture can also augment Type III and Type IV EH-BSs with non-renewable brown energy from the legacy power plant, which burns fossil fuels such as coal, oil, and natural gas to generate electricity.

As we can see, both battery and grid connection can provide a certain level of guarantee in the availability of green energy, where the battery facilitated by the *harvest-store-use* architecture can hoard the harvested energy for future use and the *grid connection* enables the wired power transfer within the whole network.

For stand alone EH-BSs, the research on green energy utilization focuses mainly on two directions: *deterministic* and *online* optimization. For various given channel conditions, traffic demands, energy arrival rates and battery capacity, the optimization of the offline transmission policy has been conducted for various system criteria, such as maximizing throughput, minimizing transmission completion time, and decreasing the brown power demand of stand alone hybrid BSs [1]. Meanwhile, for the more general scenario where knowledge of energy harvesting profiles are limited or unavailable, the design of the online transmission policy mainly focuses on balancing the complexity and the system performance using the causal information (past and present) or statistical knowledge obtained through various *learning algorithms* [3].

Instead of solely relying on the energy harvesting profiles and pursuing batteries with larger capacity, the dynamics of energy related constraints can be mitigated to a certain level through *energy cooperation*, which is enabled by the interconnection of multiple EH-BSs. From this different direction, the design of the transmission policy can be redesigned since each device's energy profiles can be manipulated; various energy sharing mechanisms within energy harvesting enabled wireless communication networks (EH-WCNs) will be discussed in the following sections.

III. WIRED ENERGY SHARING WITHIN EH-WCNS

The power supply of legacy wireless networks are mainly drawn from the power grid, which is a large interconnected infrastructure for delivering electricity from power plants to end users. Challenged by the rising energy demand, aging infrastructure, and increasing greenhouse gas emission, the traditional centrally controlled grid is being replaced by the *smart grid*, i.e., the next generation power grid in which the electricity distribution and management is upgraded for improved control, efficiency, reliability and safety Since the smart grid is envisioned as a promising technology to integrate with renewable green energy resources, it will pave the way towards a green wireless network.

A. Energy Transfer Grid

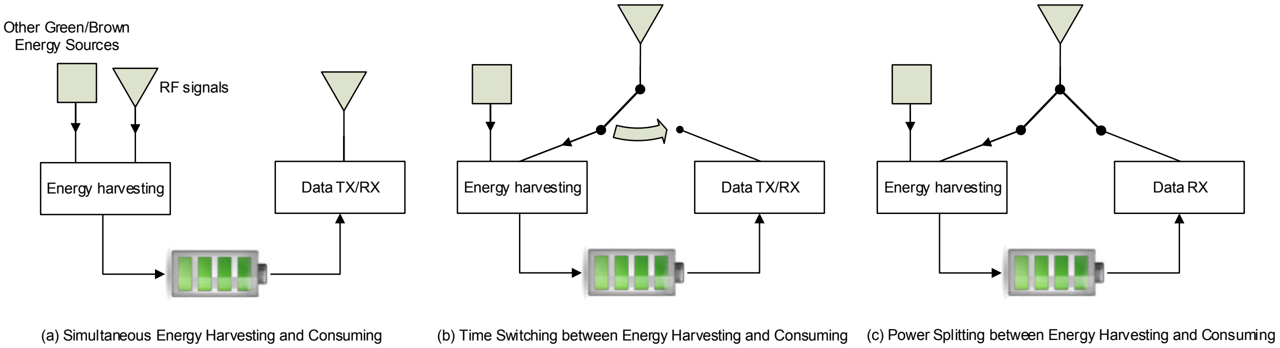
The green energy capitalization of the smart grid, whether in the form of traditional central generators or emerging distributed generators, is galvanizing worldwide. Since distributed power generators can contribute their clean energy directly back to the smart grid, the grid structure can be considered as a temporary energy storage unit.

When EH-BSs purchase energy from the power grid, the *energy price* is an important factor to balance the energy supply and demand. Current on-grid energy markets consist of *day-ahead* and *real-time* markets, where the value of the energy at the specific location and time it is delivered, i.e., locational marginal price (LMP), is calculated in different time scales [4]. LMP in day ahead market is usually settled a day in advance while the real-time market is calculated at five-minute intervals. For the emerging renewable energy market, owing to the diverse suppliers, LMP is more dynamic and sometimes even negative (when the generated energy exceeds the demand, the energy storage cost will encourage energy consumption). Hence, the wireless operator needs to design the energy flows among EH-BSs, i.e., where to purchase or sell energy, based on the available grid structure.

In considering how much energy to purchase, the wireless operator needs to take into account of the *energy loss factor*. With energy being transferred between two grid-connected EH-BSs, energy loss may be incurred due to physical properties such as resistance of transmission lines and cables between the two distributed energy harvesters, i.e., with $\epsilon \in [0, 1]$ being

TABLE I
ENERGY HARVESTING ENABLED BASE STATIONS

EH-BS		Draw/supply power from/to wired grid	Go to sleep in case of power outage
Type I	Stand Alone W/O Battery Back-up	N	Y
Type II	Stand Alone With Battery Back-Up		N
Type III	Grid-Connected W/O Battery Back-up	Y	Y
Type IV	Grid-Connected With Battery Back-Up		N



(a) Simultaneous Energy Harvesting and Consuming (b) Time Switching between Energy Harvesting and Consuming (c) Power Splitting between Energy Harvesting and Consuming

Fig. 2. Architectures of RF energy harvesting devices.

the energy loss factor, only $(1-\epsilon)$ amount of the energy can reach the destination.

B. Wired Energy Sharing Among Cellular Networks

Since small organizations are now capable of acting as energy providers, the *energy purchasing policy* and *energy sharing policy* of EH-BSs may involve multiple electricity retailers, where for each Type III or IV EH-BS, the energy purchasing/sharing policy dictates purchasing/transferring the amount of energy from/to the grid or other BSs through the grid.

As compared with traditional BSs, the deployment of EH-BSs may rely on the structure of the power grid, which impacts the efficiency of energy delivery. Zheng *et al.* [5] studied the dedicated power line model, where green energy can be transferred directly via the power line installed between any two Type III EH-BSs. Since the total energy available at each BS (the transmission power of the serving BS for each user and the interference caused by other BSs) would determine the quality of services (QoS) requirement in term of the signal to interference and noise ratio (SINR), the operation cost used to purchase power from the power grid or neighboring BSs should be taken into consideration in designing the system. While guaranteeing the minimum SINR requirement and the power outage constraint, which is characterized by the probability that the EC-constraint is violated, the overall deployment cost, including installation costs of BSs, dedicated power lines, and the operation cost, is minimized [5].

Instead of deploying dedicated power lines for each BS pair, energy aggregator can be rented by a group of BSs to form a star topology. Energy aggregator is a grid unit which allows both power injection and power withdrawal, such that the energy supply-load equilibrium can be maintained among the BSs connected to the aggregator. With the aggregator-assisted energy cooperation among cooperatively transmitting BSs, the optimal transmit power allocation and energy transfer at cooperative BSs has been proposed to maximize the downlink sumrate [6].

Since the grid structure can only store energy temporarily, the characteristics of the actual battery unit in Type IV EH-BSs, such as capacity and the corresponding energy storage cost, can be taken into account when planning the deployment of BSs/grid or designing the energy purchasing/sharing policy.

IV. WIRELESS ENERGY SHARING WITHIN EH-WCNS

Wireless energy transfer is a method of transferring electrical energy from one storage device to another without any electrical conducting media, such as plugs or wires. By exploiting a novel technique called *magnetic resonance*, Kurs *et al.* [7] showed that short range wireless energy transfer is both feasible and practical. Other methods, particularly RF microwaves and laser beams [8], have been used for long range wireless energy transfer. All these revolutionary results open a new paradigm for the energy harvesting powered wireless networks, especially the radio frequency energy harvesting (RF-EH).

A. Wireless Energy Transfer Devices

Dedicated wireless charging units, namely, *mobile charging unit* (MCU) and *stationary charging unit* (SCU), have been proposed to ensure energy delivery to the wireless nodes. MCU physically carries energy, roves around and charges the wireless nodes in need of power, while SCU is a dedicated power transmitter that can be placed at a certain location [9].

In addition to MCUs and SCUs, which solely carry energy, devices using RF signals to carry both information and energy have been designed. Three architectures shown in Fig. 2 are commonly adopted by *RF-EH enabled devices*. For the architecture equipped with separated energy harvesting and data transmission/reception modules, *simultaneous energy and information transfer* is feasible. For the architecture equipped with a co-located energy harvester and a data transmission/reception module, either *time switching* or *power splitting* can be used to schedule the RF energy harvesting and information reception processes.

The common model that captures the overall *wireless energy transfer efficiency* is given as follows:

$$E_h = \alpha\eta|h|^2 g P_t T \tag{1}$$

where E_h is the harvested energy, h is the channel condition between the EHD and the RF energy source, g is the antenna gain of both the energy transmitter and receiver, P_t is the transmission power of the RF energy source and T is the duration time of the RF signal. $0 < \alpha \leq 1$ is the portion of T or P_t that is used for RF-EH, and $0 < \eta < 1$ is the energy conversion efficiency which depends on the physical circuit of the energy harvesting device. η defines how much energy can be derived/extracted from all RF signals received by the EHD.

As we can see, for the dedicated MCU/SCU or the separated receiver architecture shown in Fig. 2a, $\alpha = 1$. Meanwhile, as far as the tradeoff between data rate and harvested energy is concerned, power splitting achieves better performance than time switching [10].

So far, RF-EH devices with low energy requirement, such as handsets and sensor nodes, are the major players of wireless energy sharing. High energy transfer efficiency and long operating range have to be achieved to practically implement wireless energy sharing among the energy demanding EH-BSs. Readers are referred to [11], [12] for detailed introduction of wireless energy transfer boosting techniques, such as antenna designs and energy beam-forming schemes.

B. Wireless Energy Sharing Among Devices

Empowered with wireless energy transfer capability, multiple RF-EH devices can act as *remote storage batteries* for each other. According to the residual energy level, RF-EH devices can be classified into *surplus nodes* or *deficit nodes*. A surplus node can replenish the battery of the mobile/static charging unit or other RF-EH devices, while MCU/SCU and surplus node can supply energy to a deficit node.

The *energy sharing policy*, which controls the transmission power P_t of each node, can be used to balance the intermittent nature of the energy sources. In general, the energy sharing policy can be divided into two categories: *uni-directional* and *bi-directional*, where uni-directional implies that energy can flow from one node to the other but not the other way around, and bi-directional means that two nodes are capable of transferring energy to each other, although not simultaneously [13], [14].

As illustrated in Fig. 3(a), the mobile charging unit moves along the *traveling path* and energy is transferred between each device and the MCU. As shown in Fig. 3(b), instead of having the MCU charging the RF-EH devices one by one, the concept of *landmark*, i.e., the placement of stationary charging units or the parking space of the MCU [15], has been proposed such that multiple devices can be charged from one location. Since the traveling path and landmark placement would affect the instantaneous energy storage of devices in the system, energy sharing policy needs to be designed along with the energy storage capacity of the dedicated charging unit and the corresponding costs, such as the one incurred during traveling.

For the system without dedicated charging units, if the complementary energy sources of RF-EH devices as shown in Fig. 2 are green, the energy sharing policy is mainly designed to maximize the system throughput, and the corresponding optimization problems have been modeled for various multi-user scenarios, such as broadcast, relay, multiple access, two-way and interference channels [3]. On the other hand, if the complementary energy sources of RF-EH devices are brown, i.e., the RF-EH devices have hybrid power sources (RF signals from which the device can harvest energy; backup non-renewable brown energy source), the minimization of non-renewable brown energy should also be taken into consideration in designing the energy sharing policy.

So far, the energy sharing policy mainly focuses on the one-hop energy transfer. In case the energy cannot be efficiently delivered from one node to the other node due to severe channel attenuation in Eq. (1), RF-EH devices can act as the *energy relays* which can transfer energy from the source to the destination via multi-hop, and the *charging route* should be designed as part of the energy sharing policy.

V. ENERGY SHARING W/O DIRECT ENERGY TRANSFER

To ensure efficient wireless traffic delivery, energy sharing within wireless communication networks has been designed for the case when there is mismatch between traffic variances and energy dynamics of each BS. Capitalizing on the broadcast nature of the wireless signals, energy sharing can be accomplished other than by direct energy transfer, through wired power grid or wireless RF energy transfer. The implicit energy sharing methods without involving direct energy transfer are referred to as *traffic offloading* and *cooperative transmission*.

Traffic offloading was first proposed to leverage unused *bandwidth* across different radio access technologies such that the system capacity can be boosted. Cooperative transmission has been proposed to enhance the cell edge throughput by allowing multiple BSs to serve the common UE simultaneously, i.e., coordinated multi-point transmission and reception (CoMP) [16]. For the EH-WCNs, traffic offloading and cooperative transmission can serve the purpose of controlling energy availability by *leveraging unused energy* among multiple BSs, i.e., offloading users to sufficiently charged adjacent EH-BSs or employing multiple energy insufficient EH-BSs to cooperatively transmit signals to one destination.

Various *UE-BS association* schemes, *sleep mode selection* schemes, and *cell size adapting* schemes have been proposed to implement traffic offloading and cooperative transmission. Han and Ansari [17] studied hybrid BS, which is the Type

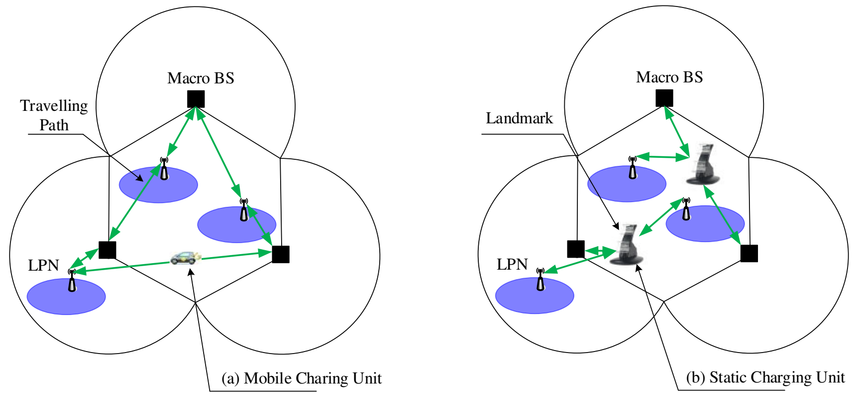
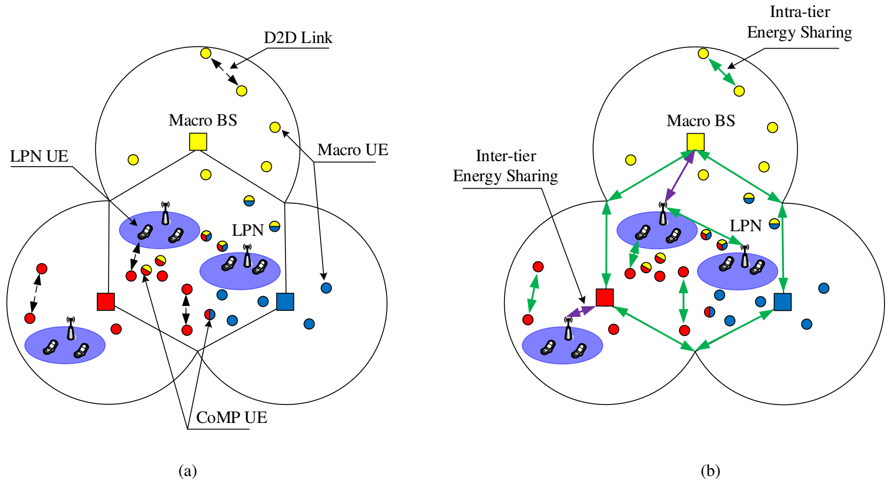


Fig. 3. Wireless Energy Sharing with MCU/SCU.

TABLE II
COMPARISON OF ENERGY SHARING MECHANISMS

Energy sharing mechanism	Direct energy transfer		Non-direct energy transfer	
	Wired energy sharing	Wireless energy sharing	Traffic offloading	Cooperative transmission
Constraints	Deployment cost of the grid architecture	Moving cost of MCU Deployment cost of SCU	Implicit energy loss due to non-max SINR association	Information exchange overhead Signal processing complexity
	Energy transfer loss ϵ	Energy attenuation $\|h\|^2$	EH-BSs involved are in close proximity	



(a)

(b)

Fig. 4. EH enabled next generation wireless communication networks: (a) data flow, and (b) energy flow.

III EH-BS equipped with an independent energy harvester and brown on-grid power. Through an UE-BS association scheme, the sum of the weighted traffic delivery latency in a heterogeneous mobile network is minimized. Zhou *et al.* [18] studied the coexistence of two kinds of BSs: traditional BS powered only by the on-grid brown energy, and Type II EH-BSs. By adjusting the BSs' active and sleep state, the average grid power consumption is minimized while the blocking probability is guaranteed, where the blocking event is caused by bandwidth depletion (traditional BS) or energy depletion (type II BS). Furthermore, for the cell size adapting scheme, the EH-BSs can decide whether to expand and cover more active users, or to shrink until entering the sleep state.

Most of the above mentioned existing non-direct energy transfer based energy sharing schemes adopt centralized UE/BS scheduling based on the instantaneous energy level of each device within the network. To take into account of energy dynamics with low complexity, energy sharing can also take the form of distributed radio resource exchange, such as energy-spectrum or energy-time trading. For example, one EH-BS with sufficient energy can take over UEs that are initially served by other BSs. In return, this EH-BS can access the spectrum that is originally occupied by other BSs, or other BSs will help deliver this BS's future traffic when their energy levels are high enough. Various credit systems can be designed for this "resource loan system".

VI. FUTURE RESEARCH TREND

As illustrated in Table IV, various energy sharing mechanisms are tailored for different application scenarios. For the wireless communication networks which have inherited the power grid structure or communication lines from legacy networks, wired energy sharing is a more promising strategy because the deployment cost is minimal and the energy loss factor ϵ is normally less than the wireless energy attenuation $|h|^2$. Wireless energy sharing is more suitable for the geo-environment where it is difficult or costly to deploy the grid structure, as compared with the moving/deployment cost of mobile/static charging units. Although non-direct energy transfer avoids the deployment cost or the explicit energy loss, its application scenario is limited to adjacent BSs due to signal attenuation of wireless channels. Furthermore, there is implicit energy loss because when the traffic offloading mechanism is adopted, it normally means the link with the maximum SINR is no longer available, and more energy will be consumed for other links.

For the next generation wireless communication networks, small, local and sustainable service providers such as diverse LPNs and device-to-device (D2D) communications as shown in Fig. 4, will likely emerge. Since multi-type EH-BSs will coexist, *heterogeneous energy sharing* may resort to the cooperation of various energy sharing mechanisms listed in Table IV. The system will hand off from one mechanism to another mechanism, or integrate multiple mechanisms simultaneously, depending on the dynamic network architecture and locations of traffic contents. Therefore, proper hand off/integration criteria need to be designed, and the complexity of the hand off/integration algorithms needs to be evaluated.

Furthermore, we have only discussed EH-BSs; energy harvesting enabled handsets will come into play when D2D communications is enabled, in which case the design of the energy sharing mechanism will likely focus on distributed wireless energy sharing schemes, energy-aware content relay schemes and other related incentive mechanisms.

VII. CONCLUSION

This article has provided an overview of major mechanisms used to control the availability of green energy across the EH enabled wireless communication networks. We have placed special emphasis on energy sharing mechanisms, which can rectify the mismatch between energy dynamics and traffic variations. For the next generation wireless communication networks, the versatile and flexible network architecture will require hand off or integration among multiple energy sharing mechanisms, new energy sharing mechanisms such as content relay among EH-UEs and the corresponding incentive design, and distributive energy sharing mechanisms for small, local service providers. This article will hopefully help readers jump start further research in provisioning energy harvesting enabled next generation wireless communication networks.

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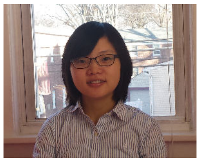

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