Dynamic Energy Trading for Wireless Powered Communication Networks

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Abstract

Wireless powered communication systems attract significant interest recently because of its potential to provide a ubiquitous and sustainable energy supply for communication networks. However, the energy that can be harvested from external energy sources is generally uncontrollable and intermittent. By allowing multiple devices to exchange their harvested energy, dynamic energy trading (DET) is introduced to improve the energy supply reliability and performance of the wireless powered communication networks. This article provides an overview on the possible architecture and functional components that enable DET in communication networks. Various design issues on how to implement DET into practice are discussed. An optimal policy is proposed for delay-tolerant wireless powered communication networks in which each wireless powered device can schedule its data transmission and energy trading operations according to the current and future energy availability. Finally, some potential topics and challenges for future research are highlighted.

I. INTRODUCTION

By allowing electric devices to harvest energy from the natural environment such as solar, wind, radio wave and vibration, energy harvesting is a promising technology to provide ubiquitously available and green alternative energy sources for communication devices. However, the uncontrollability, uncertainty and unpredictability of external energy sources in

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the natural environment make it difficult to provide a reliable power supply for communication networks. Recent works on wireless power transfer suggest that it is possible to allow a certain amount of energy to be transferred from dedicated energy sources to each device to support high energy consuming services. This significantly widens the possible applications for wireless powered communication systems. For example, Stanford University's Global Climate and Energy Project has recently reported that it is possible to deliver up to 10 kilowatts of power for a distance of 6.5 feet with transfer efficiency of around 40% which has the potential to be applied in the parking lots or highways to wirelessly charge electric vehicles in the future [1].

Motivated by the observations that the combination of energy harvesting and wireless power transfer can take advantage of both technologies to further improve the system reliability and energy utilization efficiency, the energy harvesting and wireless power transfer-enabled systems have attracted significant interest in the communication research community. For example, the concept of network-assisted energy harvesting has been studied in [2] for a wireless power supply network consisting of a set of dedicated energy stations that can wirelessly transfer electric power to mobile devices coexisting and telecommunication networks. Each mobile device can coordinate with each other by utilizing the telecommunication networks and obtain reliability guaranteed wireless power supply from its nearby energy stations.

In this article, we introduce a new concept, referred to as *dynamic energy trading* (DET), for wireless powered communication networks. DET allows multiple wireless powered devices (WPDs) with temporal and spatial variations in their energy harvesting processes to negotiate and exchange energy with each other. In DET, the WPDs that obtain more energy than they can consume can transfer their surplus energy to those who cannot receive sufficient energy to support the required services. Compared to the existing energy harvesting and wireless power transfer-enabled systems, DET possesses the following benefits:

1) It is known that the energy harvested from the natural environment is intermittent and time-varying. DET allows the WPDs with different harvestable energy to help each other and hence can further improve the reliability of the power supply for wireless powered communication networks.
2) Most existing works focus on the wireless power transferred from a dedicated energy source to a fixed energy receiver. DET allows different WPDs with different harvestable energy

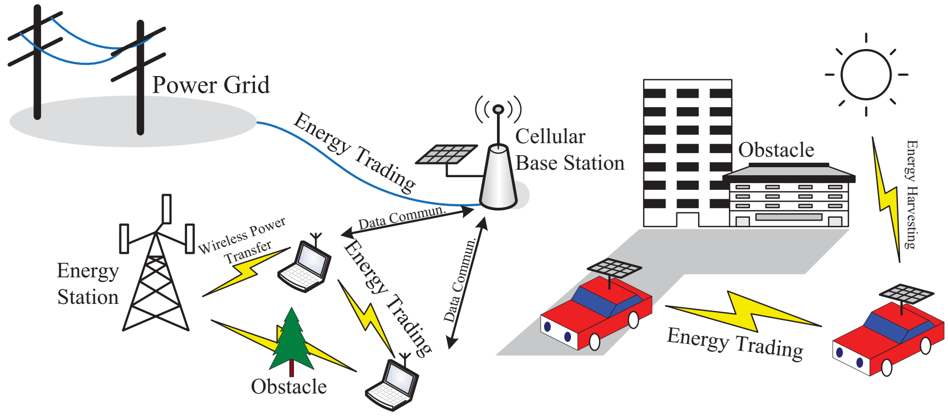

Fig. 1. Dynamic energy trading in wireless powered communication networks: we illustrate three possible scenarios of energy trading: 1) energy trading between a power grid and a cellular base station, 2) energy trading between two wireless powered cellular mobile devices, and 3) energy trading between two solar-powered electric vehicles.

to dynamically exchange energy among each other. It can mitigate the energy wasting and increase the energy utilization efficiency for wireless powered systems without requiring the investment on dedicated power supply network infrastructures.

II. Architecture and Operations for DET

A. Architecture of DET

In this article, we focus on the energy trading among multiple WPDs. Each WPD can correspond to a hardware equipment which belongs to a part of the permanently deployed infrastructures such as fixed energy stations (e.g., power beacons [3]). It can also be a portable device with energy transfer and receiving hardware. It is known that the energy that can be harvested by each WPD depends on various factors such as the location and orientations of energy harvesting equipments (e.g., antennas and solar panels), energy conversion efficiency, and distance to the external energy sources. Therefore, even closely located WPDs may harvest significantly different amount of energy at the same time. DET has the potential to further improve the energy utilization efficiency by allowing the WPDs that can harvest more energy than they can use to sell their surplus energy to the WPDs that cannot harvest sufficient energy to support required services. Depending on the energy delivery facilities, energy trading can be divided into two types:

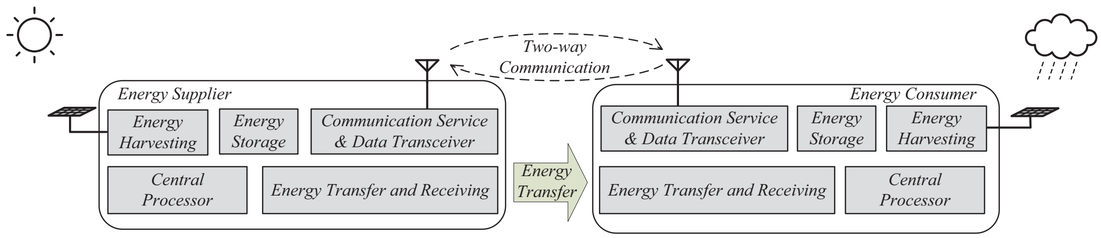

Fig. 2. Diagram of WPDs in an energy trading-enabled system.

1) Wired Energy Trading: WPDs are connected with the wired two-way power delivery infrastructure such as power grid and power transmission line and can exchange and trade energy with each other [4], [5].
2) Wireless Energy Trading: In the case that WPDs are not connected with each other through wired power delivery infrastructure, they can exchange and trade their obtained energy through wireless power transfer.

In this article, we mainly focus on the wireless energy trading. To simplify our description, we assume that the data communication, energy harvesting and trading processes are time-slotted. In each time slot, the number of data packets received by each WPD, and energy that can be harvested and traded among WPDs are assumed to be fixed. To simplify our description, we normalize the duration of each time slot into unity and can therefore use the terms "energy" and "power" interchangeably. In each time slot, WPDs are divided into two types:

- *Energy suppliers* are the WPDs that can provide controllable amount of energy supply to other WPDs. Energy suppliers can be WPDs within a power delivery infrastructure such as the electrical generators and power grid or dedicated energy sources deployed by the network operators or utility companies. They can also be mobile WPDs with surplus energy that can be transferred to their nearby WPDs.
- *Energy consumers* are the WPDs that cannot obtain enough energy to support the required service without requesting a certain amount of energy to be transferred from the energy suppliers.

In DET, the sets of suppliers and consumers can change dynamically. Figure 1 illustrates several possible applications of DET in a wireless powered communication system.

The block diagrams of two WPDs corresponding to an energy supplier and an energy consumer in a wireless energy trading system are illustrated in Figure 2. A WPD can have an *energy harvesting module* to convert external energy in the natural environment into electric current. The converted electric current will then charge an *energy storage module* which can correspond to a (super) capacitor or rechargeable battery. If the WPDs also need to fulfill the required data communication service, they will include the *communication service module* which consists of a data arriving queue to store arrived data packets. The *data transceiver module* provides data transmission and receiving functions for the communication service module to send the required data signals as well as the two-way negotiation and communication between suppliers and consumers during the energy trading. Both the *energy transfer and receiving modules* include matching circuits which can adjust the energy transfer and receiving parameters such as the transmit energy level, and transmission and receiving frequency. The *central processor module* plays a vital role in the energy trading process between suppliers and consumers, i.e., it will decide which consumers or suppliers and how much energy to trade according to the energy level of its battery, harvestable energy, energy requested by the consumers, arrival rate of data packets, required quality-of-service (QoS) and other information such as the knowledge about the future change of energy harvesting processes. Note that in some systems, the energy receiving module and energy harvesting module can be the same. For example, if WPDs have installed with the radio frequency (RF)-based energy harvesting equipments, it can receive the RF energy transferred from other WPDs using the energy harvesting module.

We use term *mode* to describe the decision made by each WPD about operating as the supplier or consumer in each time slot and refer to the process for each WPD to decide its mode as the *mode selection*.

B. Energy Trading Operations

A DET process includes the following operations: each WPD will first decide its mode as supplier or consumer. Each supplier (or consumer) will then try to discover the identities and information about energy availability of its neighboring consumers (or suppliers). A two-way communication link can be established between each supplier and its neighboring consumers to negotiate details of energy trading. Once an agreement has been reached, the agreed amount of energy will be transferred from the suppliers to the consumers. The possible energy trading

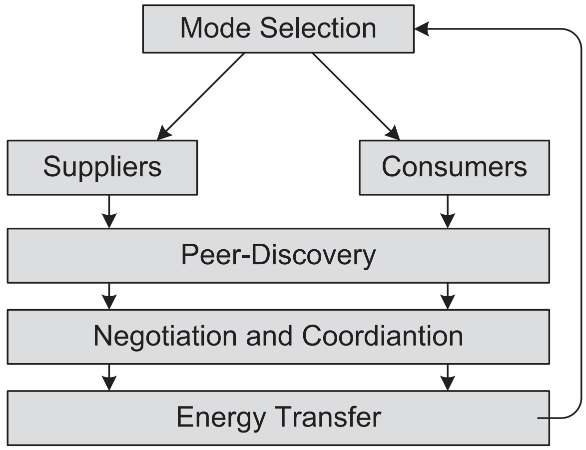

Fig. 3. Energy trading operations.

operations are illustrated in Figure 3. Let us give a more detailed discussion on each of these operations as follows.

1) Mode Selection: As mentioned previously, the mode of each WPD can change dynamically. Therefore, it is important for each WPD to first decide its mode by evaluating the energy that it can obtain as well as that should be spent on supporting the required service. Each WPD can also take into consideration of the existing and future energy consumption of its installed modules. In [6], the authors studied a simple mode selection rule in which each WPD will first decide its mode by comparing the current harvestable energy to the data transmission requirements. The WPD can then operate as the supplier if there is surplus energy after the required service has been fulfilled or operate as the consumer otherwise. In [7], each WPD will select its mode by also taking into consideration of the evolution of the possible harvestable energy and energy that can be traded with other WPDs in the future.

2) Peer-Discovery and Coordination: Once each WPD has selected its mode, it will then discover the identity of suppliers or consumers in its surrounding area. The peer-discovery approaches for the WPDs can be classified into *distributed discovery* and *network-assisted discovery*. In the distributed discovery, each consumer (or supplier) autonomously discovers the identity of its neighboring suppliers (or consumers). A simple peer-discovery protocol has been proposed in [7] in which each supplier broadcasts its available energy and unit price for energy transfer at the beginning of each time slot. Each consumer can then send its bid for the required amount of energy to its preferred suppliers. If a supplier accepts the request of the consumer, it will start transferring the requested amount of energy at the agreed time and frequency. Otherwise, the supplier will simply ignore the energy requests of the consumers. The consumers will update its belief about whether the suppliers will accept its requests and will only send request to those suppliers that have high chances to accept its energy request in the future. In the network-assisted discovery approach, each WPD discovers the nearby consumers or suppliers using the information provided by the network operator or the central controller.

3) Negotiation and Information Exchange: Once an agreement has been reached between an energy supplier and a consumer, they will form an energy trading pair. The consumers will decide how much energy to request from the suppliers based on the energy required to support their service and the cost for trading energy with each supplier. Each supplier can impose a price for each unit of energy transferred to the consumers [8]. This will not only incentivize the suppliers to sell their surplus energy but could also avoid each consumer to request unnecessarily large amount of energy from the suppliers.

4) Energy Transfer: Once an agreement has been reached between suppliers and consumers, the suppliers will start sending the energy with the agreed amount to the consumers. Since each energy supplier or consumer has unique properties with specific hardware requirement, the energy that can be transferred and successfully received depends on the specification of the installed power transfer and receiving hardware. For example, if the energy transfer between the suppliers and consumers has been achieved by wireless power transfer technologies, such as inductive coupling, RF energy transfer, or (strongly) coupled magnetic resonance, the energy loss during the wireless power transfer will be affected by the distance between suppliers and consumers, the energy transfer frequency, circuit design, antenna orientation, etc.

III. Design Issues for DET

In this section, we discuss the possible issues to design an energy trading-enabled system.

A. Energy Transfer and Usage Scheduling

Energy scheduling means that each WPD should "prepare for the future" by taking advantage of the knowledge about the future evolution of the natural environment. For example, a WPD can save some of its currently harvested energy for future use if there is a high chance that, during the next period of time, the harvested energy will be inadequate to support the required communication services.

The energy usage scheduling scheme and the resulting performance gain depend on the knowledge about the future energy harvesting process at the WPDs. An optimal scheduling policy has been derived in [9] by assuming that the future change of the harvested energy has the Markov property and the statistical feature of the transition between different levels of harvested energy can be perfectly known by each WPD. If the WPDs cannot know the probability distributions of the future evolution of the energy harvesting process, they can learn this information from the past experience. In this case, there is a fundamental tradeoff between how to take advantage of the knowledge that has already been learned by WPDs to maximize performance (exploitation) and how to explore the new knowledge to further improve the energy scheduling gain (exploration). It has been shown in [10] that by applying the Bayesian reinforcement learning approach for each WPD to learn the statistical features of the energy harvesting process, the above tradeoff can be solved by allowing each WPD to sequentially optimize its energy scheduling scheme to maximize its long-term performance.

B. Interference Management

Interference has been regarded as one of the main factors that deteriorate the QoS for wireless communication services. However, the interference can also be regarded as one of the potential energy sources which is beneficial especially for the WPDs with RF energy harvesters [11]. A communication system powered by energy harvested from the ambient backscattered RF signals has been developed in [12] in which a prototype has been built to achieve 1 kbps transmission rate over distances of 2.5 feet and 1.5 feet in outdoor and indoor environments, respectively.

C. Simultaneous Wireless Information and Power Transferring (SWIPT)

In SWIPT, the data communication signal can piggyback the energy signal sent to the WPDs [13]. SWIPT opens new opportunities to jointly analyze and optimize the wireless data communication and power transfer problems. Initial studies assume that both energy and information can be transferred using the same signal. Recent observations suggest that simply transferring energy and data signal simultaneously over the same frequency may result in intolerable interference to the data signal in most practical systems. How to efficiently split the energy and data signal during communication and achieve the optimal tradeoff during the signal transmission and wireless power transfer is one of the main challenges in SWIPT [3].

D. Energy Beamforming

It has been observed that if an energy supplier is deployed with multiple antennas, it can steer the energy transfer signal toward a specific direction. Energy beamforming can be further categorized into MIMO beamforming and distributed beamforming. In MIMO beamforming, the transmitter is installed with multiple antennas, and hence can change the angle of power transfer by adjusting the energy signals and power levels at each antenna [3]. In the distributed beamforming, two or more energy stations can coordinate with each other to emulate an antenna array by transmitting a common energy signal in the direction of intended energy consumers. The distributed beamforming requires communication and coordination among multiple energy suppliers which may result in energy transferring delay. It does, however, allow energy beamforming to be achieved for single-antenna WPDs.

E. Energy Cooperation

It is known that both data and energy transferring signals deteriorate significantly with the increase of the transmission distance. To alleviate this problem, WPDs can cooperate with each other to relay data and/or energy signals for each other. Existing multi-hop relaying protocols such as amplify-and-forward and decode-and-forward have already been extended into energy relaying in [14]. Motivated by the fact that different relay nodes can result in different energy and data transferring efficiency, the relay selection problems were studied in [8].

IV. An Optimal Policy for Wireless Powered Delay-Tolerant Communication Network with DET

A. System Models

Consider a communication network consisting of multiple WPDs each of which is equipped with both energy transfer and receiving modules to exchange energy with others. At the beginning of each time slot t, each WPD i receives $\hat{u}_{i,t}$ data packets and knows the amount of energy $\hat{e}_{i,t}$ that can be harvested during the rest of the time slot t.

Each WPD i has a data buffer and a battery that can store no more than $\bar{u}_i$ data packets and $\bar{e}_i$ units of energy, respectively. We assume that the data transmission is delay-tolerant, and each WPD can intentionally delay the transmission of some data packets if it believes that it will obtain more energy and/or will have fewer data packets to transmit in the future. Due to the limit of the buffer size, if the number of newly arrived and buffered data packets exceeds the size of buffer, some of the data packets will be dropped. In particular, the number of data packets that WPD i has to be dropped at the beginning of time slot t is given by $l_{i,t} = \max\{u_{i,t}+\hat{u}_{i,t}-\bar{u}_i, 0\}$ where $u_{i,t}$ is the buffer level of WPD i at the beginning of time slot t given by $u_{i,t} = \min\{u_{i,t-1}+\hat{u}_{i,t-1}, \bar{u}_i\} - v_{i,t-1}$, and $v_{i,t-1}$ is the number of data packets sent by WPD i during time slot $t-1$. The battery level of WPD i is given by $e_{i,t} = \max\{e_{i,t-1}+\hat{e}_{i,t-1}-w_{i,t-1}, \bar{e}_i\}$ where $w_{i,t-1}$ is the energy spent on transmitting data packets in time slot $t-1$.

Each WPD needs to send the received data packets to its corresponding destination with the required QoS. We assume that there is a one-to-one mapping function $f(\cdot)$ from the number of transmit data packets $v_{i,t}$ to the amount of energy $w_{i,t}$ that should be spent in sending $v_{i,t}$ data packets with the required QoS. Each WPD can receive reward $\alpha_{i,t}v_{i,t}$ by successfully sending $v_{i,t}$ data packets and will incur cost $\beta_{i,t}l_{i,t}$ for losing $l_{i,t}$ data packets in each time slot t where $\alpha_{i,t}$ and $\beta_{i,t}$ are the reward and cost of successfully sending and dropping each data packet, respectively. We assume that each WPD can always discover its nearby consumers and suppliers, and each consumer (or supplier) has already been assigned with a supplier (or consumer).

Each WPD i will decide the following parameters at the beginning of each time slot:

1) If WPD i chooses to operate as the supplier ($m_{i,t} = 0$), then it will decide how much energy $\Delta q_{i,t}$ to be sent to the consumers. We assume that WPD i can receive $\lambda_{i,t}\Delta q_{i,t}$ reward for selling $\Delta q_{i,t}$ energy units where $\lambda_{i,t}$ is the price for selling each unit of energy.
2) If WPD i chooses to operate as the consumer ($m_{i,t} = 1$), then it will decide how much energy $\Delta q_{-i,t}$ to request from the supplier. In this case, WPD i will pay $\rho_{i,t}\Delta q_{-i,t}$ to the suppliers for transferring $\Delta q_{-i,t}$ energy units where $\rho_{i,t}$ is the price per unit of energy sent by the suppliers.

We can write the payoff of WPD i in time slot t as $\varpi_{i,t}\left(v_{i,t}, l_{i,t}, m_{i,t}, \Delta q_{i,t}, \Delta q_{-i,t}\right) = \alpha_{i,t}v_{i,t} - \beta_{i,t}l_{i,t} + \left(1-m_{i,t}\right)\lambda_{i,t}\Delta q_{i,t} - m_{i,t}\rho_{i,t}\Delta q_{-i,t}$.

B. An Optimal Policy

We can formulate the decision making process for each WPD i in a DET system as a Markov decision process (MDP) with infinite horizon consisting of the following elements:

- *State space* $\mathcal{S}$ is a finite set of the possible energy levels that can be harvested and the data packets required to send.
- *Action space* $\mathcal{A}$ is a finite set of possible number of transmit data packets, the mode selected by WPD i, and possible energy that can be sent to the consumer if WPD i operates in the supplier mode or possible energy that can be requested from the suppilers if WPD i operates in the consumer mode.
- *State transition function* $\mathcal{T} : \mathcal{S} \times \mathcal{A} \times \mathcal{S} \rightarrow [0,1]$ specifies the probability distribution that, starting at state s_i using action a_i, the state ends in s'_i. This transition function can be estimated from the system model or obtained from the past experience. In this article, we follow a commonly adopted assumption that the state transition function can be known by each WPD.

The main objective for each WPD is to find a decision policy π which maps the current state to action. We can therefore write the objective function of the joint optimization problem as follows:

$$\max_{\pi} \lim_{t\rightarrow\infty} \frac{1}{t} \mathbb{E}_{\pi} \left[\sum_{l=1}^{t} \varpi_{i,l} \left(a_{i,l}, s_{i,l} \right) \right]. \tag{1}$$

This optimal policy can be calculated numerically using the standard value iteration or policy iteration algorithms.

C. Numerical Results

We evaluate the performance of our proposed energy trading policy by considering a WPD that can harvest up to 10 mW of energy from the natural environment and send or request up to 10 mW to or from its nearby WPDs during each time slot. The battery of the WPD can store up to 20 mW. Energy transfer efficiency can be different with different wireless power transfer technologies. In this section, we assume that the energy transfer efficiency is 0.5. For example, it has been shown that a WPD is equipped with a self-resonant coil and can transfer energy with others using strongly coupled magnetic resonances at a distance up to 180 cm [15]. The WPD can transmit up to 20 mW of power during each time slot. We assume that the minimum amount

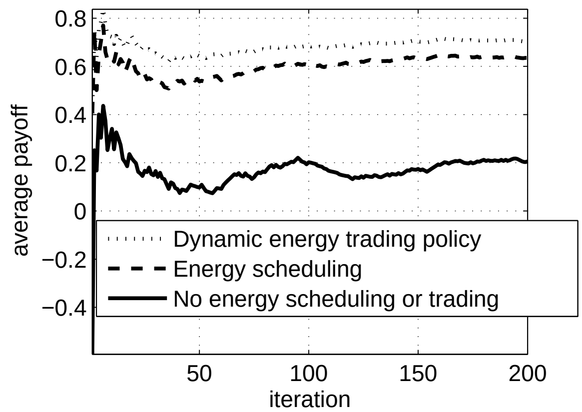

Fig. 4. Comparison of the average payoff of a WPD with DET policy, energy scheduling and no energy scheduling and trading under different iterations.

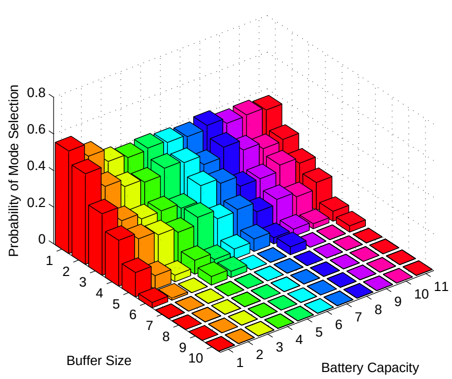

Fig. 5. Probability of WPD i to operate in supplier mode.

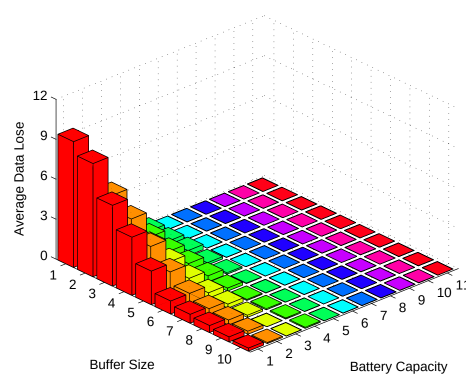

Fig. 6. Average number of data packets lost.

of energy harvested and requested as well as transferred is 1 mW and the minimum amount of energy required to send each data packet is 0.5 mW.

We compare the average payoffs achieved by our policy and the optimal energy scheduling approach [9] without energy trading in Figure 4. If the WPD uses neither energy scheduling nor trading, it will simply transmit signals with the harvested energy. We can observe that our proposed policy jointly optimizes the mode selection, energy scheduling and trading and hence achieves significant performance improvement compared with the traditional energy harvesting system without DET. In Figures 5 and 6, we compare the probability for each WPD to decide to operate as the supplier and the average data packet loss under different buffer and battery sizes. We can observe that DET significantly improves the reliability of the data transmission especially when each WPD can have the large battery and data buffer sizes.

V. Challenges and Future Research Topics

DET opens many promising new applications in the future development of wireless powered communication networks.

A. Potential Research Topics for Energy Source Discovery

Future networks will consist of high density of WPDs coexisting with various types of network infrastructures including the cellular BSs and Wi-Fi access points. It is important to develop an efficient protocol for each WPD to quickly discover the identities of neighboring suppliers or consumers with the assistance of the network infrastructure. For example, each WPD can report its identity and mode to its closest cellular BS. Each BS can then assign each consumer with the appropriate supplier and inform the pairing results to other WPDs within its coverage area. In addition, the network infrastructure can also help to regulate the energy trading among WPDs. For example, the cellular BSs can broadcast a warning signal in the frequency bands before transmitting data signals. Each supplier should stop sending energy signals whenever it receives the warning signals sent by the BSs.

B. Potential Research Topics for Energy Scheduling

It is known that if WPDs can have the prefect knowledge about the future evolution of the energy harvesting process, it can further improve its performance by optimally scheduling its energy usage. However, in practical systems, it is generally impossible to always accurately predict the statistical features of the future energy harvesting and transfer processes. It is therefore important to develop a unified framework that can characterize the relationship between the accuracy of the prediction and the performance gain achieved by the energy scheduling.

C. Potential Research Topics for Energy Transfer and Offloading

The total amount of harvestable energy within a given time duration is always limited. It is possible that the total amount of energy requested by the consumers exceeds the limit. A fairness criteria and mechanism should be designed to properly and fairly divide the energy among consumers according to the amount of energy requested by each consumer, energy trading costs and hardware specification of each supplier.

In addition, some suppliers will be overloaded if the number of consumers requesting for the energy transferring exceeds their maximum limit. Therefore, how to propose a simple and distributed mechanism to offload the energy requests of some consumers to other nearby suppliers is an interesting topic that worth further investigation.

D. Potential Research Topics for Cost Evaluation and Pricing Mechanism

The data transmission requirement and harvestable energy of each WPD can change dynamically. Therefore, different WPDs will have different requirements for energy trading during different time slots. It is important for each WPD to properly evaluate its benefits and costs before trading energy with other WPDs. One possible solution is to introduce a virtual currency among energy trading WPDs. In this case, each supplier should decide a proper price for its transferable energy and broadcast the price to the potential consumers at the beginning of each time slot. Each consumer should then evaluate the price broadcasted by the suppliers and choose the suppliers with the most affordable price to purchase energy. How to design an efficient pricing mechanism that can incentivize the energy trading among WPDs and avoid some WPDs to benefit from cheating their prices is still an open problem.

VI. Conclusion

This article has presented an overview of DET and its possible implementations into the paradigm of wireless powered communication systems. We have introduced a general architecture and described the potential functional modules that enable the energy trading in network systems. The design issues that can implement DET in practical systems have also been discussed. We have studied a delay-tolerant wireless powered communication system as an example to demonstrate how to optimize the energy trading in communication networks. An optimal policy has been developed for each WPD to sequentially decide its mode, transmit data packets and the amount of energy traded with others. We have presented numerical results to justify the performance improvement that can be brought by DET and discussed the future research topics. Currently, both energy harvesting and wireless power transfer are still in the early stage of developments.

This article can serve as a step stone for a wider range of researches in future generation of environmental-friendly wireless powered communication networking systems.

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