A Survey of Energy Harvesting Communications: Models and Offline Optimal Policies

Yejun He, Xudong Cheng, Wei Peng, and Gordon L. Stüber

ABSTRACT

As people pay more attention to environmental protection and energy conservation issues, energy consumption in communications have become a hot research field. In wireless communications networks such as wireless sensor networks, traditional battery-operated devices or nodes have a short lifetime and die after the batteries are depleted, and replacing the batteries may be very costly and sometimes will be impossible. Therefore, energy harvesting (EH) communications have become a good means to solve this problem. EH communications mean the nodes can continue working by harvesting ambient energy. EH communications are different from the traditional battery-operated communications, so we need new models and optimal transmission policies to maximize the throughput. In this article we review different methods of harvesting the ambient energy in EH communications and the models of EH communications. We focus on offline optimal policies, then compare different policies and classify them into certain types. Finally, we propose several open research challenges and directions for future work.

INTRODUCTION

With the widespread deployment of wireless networks and devices, energy consumption management in wireless devices has become a recent topic of interest. Some wireless network devices, such as cellular phones, can maintain operation by simply charging or changing their batteries, a process that may be very difficult for other types of wireless network devices. For example, with wireless sensor network deployments, the sensor area may be large and the sensors randomly located, so the replacement of sensor batteries after the batteries have been depleted is expensive or impossible. Energy harvesting (EH) approaches have been proposed for such cases, whereby the lifetime of wireless devices is extended by harvesting ambient energy.

Energy harvesting devices can harvest ambient energy from sources such as the sun, radio waves, and vibration [1], and turn these sources into electricity for usage or storage. With the development of integrated circuits and other low-power electronic devices, energy harvesting technologies are entirely feasible. A new Energy harvesting-Communication networks: OPtimization and demonStration (E-CROPS) project began its work in February 2013 [2]. The project is funded by European coordinated research on long-term CHallenges in Information and Communication Sciences and Technologies-European Research Area-net (CHIST-ERA), whose purpose is to use energy harvesting and smart energy management technologies in communication and mobile devices to achieve an optimal balance between the quality of service (QoS), performance, and efficient use of energy.

Energy harvesting technologies can be used in a wide range of applications, including wireless sensor networks, building automation networks, machine to machine communications, and the smart grid [3]. Such wireless networks can become self-sustaining and maintenance-free by using EH technology to prolong the lifetime of the network devices. EH devices operate by harvesting ambient energy, which is fundamentally different from the traditional battery-operated devices. Battery-operated devices have a fixed amount of reliable energy, whereas EH devices harvest a random and uncertain amount of energy. Therefore, it is critical to optimize the transmission policy for EH devices. Optimal transmission policies are required for efficient usage of harvested energy, to maximize the amount of transmitted data by a given deadline or to minimize the transmission completion time by making full use of the energy.

For a single-hop model, Yang and Ulukus [4] derived the optimal packet scheduling policy to minimize the transmission completion time and gave some important lemmas for designing the optimal policy. Ozel *et al.* [5] suggested a *directional water-filling* algorithm that takes into account both the channel condition and energy capacity to maximize the throughput. Orhan *et al.* [6] proposed a *directional glue pouring* algorithm to compute the optimal policy with processing energy cost for communication on a fading channel. Maria and Miquel [7] suggested

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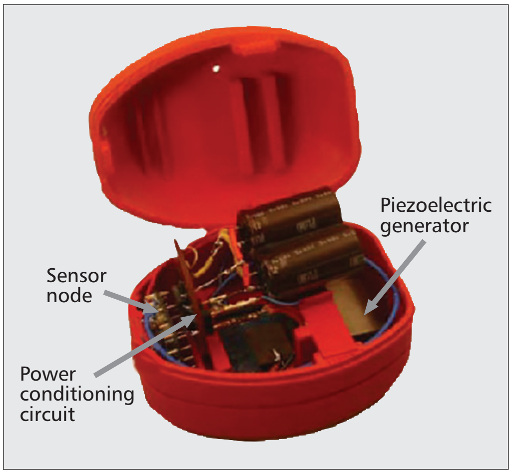

Figure 1. A real EH node [10].

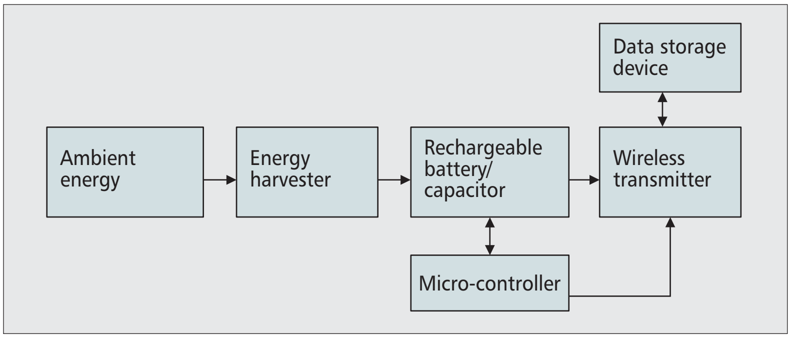

Figure 2. Practical model diagram of EH systems.

using a QoS constraint to prevent battery overflows.

For a two-hop EH communications model, Yaming Luo *et al.* [8] proposed an improved *directional water-filling* algorithm that maximizes throughput. Deniz and Bertrand [9] considered both full-duplex and half-duplex communication with an EH relay node in the two-hop model.

This article presents an overview of the optimal transmission policies in EH communications. Different methods of harvesting ambient energy and the models of EH communications are reviewed, with a focus on off-line optimal policies. Finally, we discuss several open problems and propose future research challenges and directions.

Methods of Energy Harvesting

Many sources of ambient energy that can be harvested and used, for example, piezoelectric harvesting devices, can convert mechanical energy into electrical energy, and we can see a real EH node in Fig. 1. Different types of harvesting devices can scavenge for different kinds of energy such as solar, radio-frequency, thermal energy, etc. However, the amount of available energy to be harvested varies over space and time. Solar energy is available in the daytime while it vanishes at night, and radio frequency energy may be available in urban areas, while wind energy is available in open areas. Hence, it is very important to choose the appropriate energy harvesting method based on the network's energy harvesting environment. Table 1 lists various energy harvesting methods and their power generation capability [1].

A practical model diagram for EH systems is shown in Fig. 2. The energy harvester converts ambient energy into electrical energy, which is stored in the rechargeable battery or capacitor, which is called the energy buffer. The rechargeable battery or capacitor in turn provides power for the micro-controller and transmit module. The micro-controller can manage the entire node, including power supply, information to transmit or receive. Usually, there is a data storage device that is called the data buffer to store the data that have been harvested but not yet transmitted.

System Model

There are two different approaches for designing optimal transmission policies: online and offline. With online approaches, the nodes only have statistical knowledge of the energy harvesting process, while offline approaches assume that the node has full knowledge of the amount and arrival time of the harvesting energy. Offline approaches are an idealistic situation, but can

Energy source	Power density	Advantages	Disadvantages
Solar	15 mW/cm^3	Sufficient energy in the daytime, high output voltage	Disappear at night
Vibration (piezoelectric)	200 uW/cm^3	Without voltage source	Brittle materials
Thermoelectric	40 uW/cm^2	Long life, reliable with low maintenance	Low energy conversion efficiency
Acoustic noise	960 nW/cm^3	High energy conversion efficiency	Rare environments with high acoustic noise levels
Airflow	1 mW/cm^2	Sufficient in certain place and time	Big size
Radio frequency	1 uW/cm^2	Sufficient in urban areas	Few in suburbs

Table 1. Comparison of different harvesting methods [1].

provide analytical and heuristic solutions for designing the optimal transmission strategy [7]. Many studies have been done to analyze point-to-point offline optimal transmission policies. The entire collection of EH communications models may be classified into single-hop models, two-hop models, and multi-hop models. A single-hop EH communications model is shown in Fig. 3a. The transmitter is an EH node having a data queue and an energy queue, where both the data and the energy are packetized, such that the EH communications process is modeled as a packet arrival and transmit process.

We define E_i as the amount of energy from the ith energy harvesting and B_i as the number of bits in the ith data packet arrival. The total energy consumed by the transmitter up to this time t is $E(t)$, while the total transmitted data is $B(t)$. Then $E_{\max}$ denotes the energy buffer capacity and $B_{\max}$ denotes the data buffer capacity, which are the red lines in Fig. 3a, where the energy and data that exceed the red lines must be discarded. Let the rate-power function $r(p)$ be the transmission rate at a transmission power $p(t)$; we also define $h(t)$ as the channel state information (CSI), and $r(p)$ is a non-negative, monotonically increasing and strictly concave function as shown in [3, 5, 6].

The single-hop model is a simplified situation that admits easier analysis. However, in many scenarios, the channel condition from the source (transmitter) to the destination (receiver) is such that the source node cannot transmit data directly to the destination node. In this case, a relay node is needed for data storage and forwarding, resulting in a two-hop or multi-hop transmission. Figure 3b shows the two-hop EH communications model, where E_i^s is the amount of energy from the ith energy harvesting at the source node, and E_i^r denotes the amount of energy from the ith energy harvesting at the relay node. The multi-hop model in Fig. 3c is more realistic and complicated, and we can divide it into simplified single-hops for analysis.

In energy harvesting communications transmission policies, there are two causality constraints for all the models: the energy may not be used before it is harvested, and the data packet cannot be delivered before it has arrived [4]. The total consumed energy cannot be more than all the harvested energy, and the total transmitted data cannot be more than all the arrived data, which is very different from battery-operated systems. If we consider the energy buffer capacity and data buffer capacity as finite, we must guarantee that the instantaneous energy and data cannot be more than the capacity; otherwise, some energy or data may be lost, resulting in suboptimal policies.

In the case of battery-operated devices, there is an initial amount of energy in the battery, and no energy is harvested. It can be proven by using Jensen's inequality that transmitting at a constant power will maximize the total transmitted data B by the deadline T [3]. An important factor that determines the performance of an EH system is the EH profile, which models the variation of the harvested energy with time [11]. The EH profile is depicted in Fig. 4. In Fig. 4a, if we have total $4E$ energy at time $t = 0$, the red dashed line is

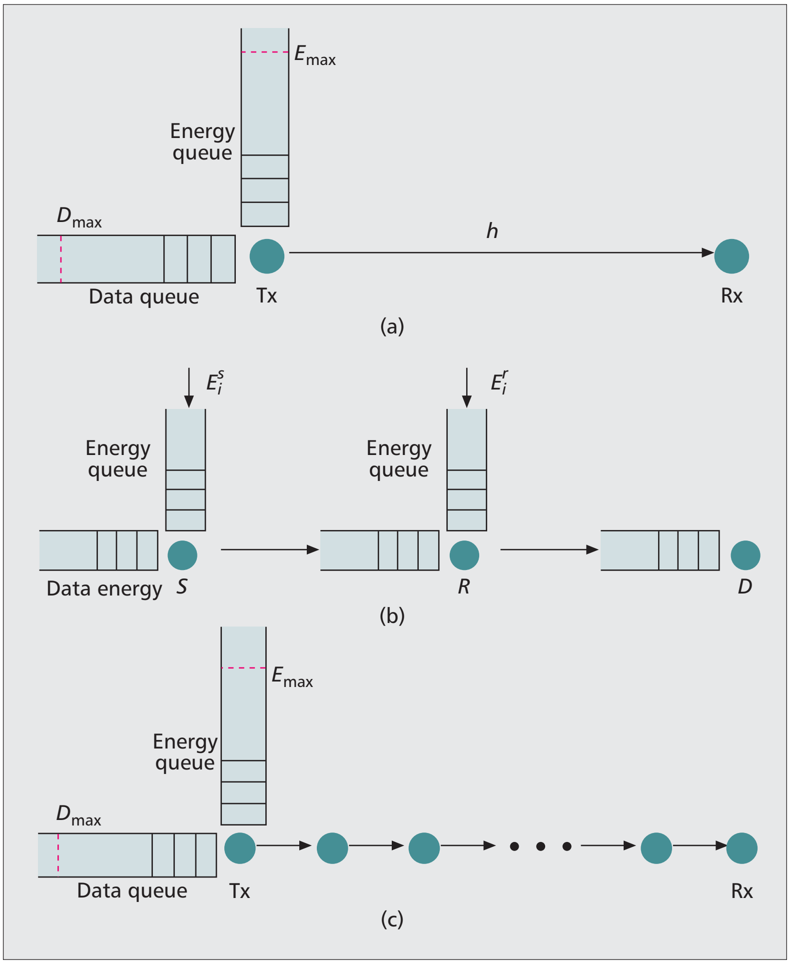

Figure 3. EH communications models: a) single-hop model; b) two-hop model; c) multi-hop model.

the best policy because it transmits at a constant power and finally uses up all the energy and the slope of the line corresponds to the transmit power. However, the red dashed line is impossible for EH communications systems, because the red dashed line has an intersection with the energy harvested line, which violates the energy causality constraint. So the feasible policies for an EH system fall under the black thick solid lines, such as the green thin solid lines.

Offline Optimal Policies

In this section we survey point-to-point EH communications optimal offline policies, which include the single-hop and two-hop models. In a single-hop model the transmitter sends data to the receiver directly over a wireless channel; in a two-hop model the transmitter uses a relay node to forward its data to the receiver.

Single-Hop Model

For a single-hop model, the goal is to minimize the transmission completion time T by when all packets are delivered to the receiver. Yang and Ulukus [4] discussed the optimal packet scheduling policy for minimizing the time T, and it has two scenarios. One scenario is when there are a total of B bits available at time $t = 0$ and no

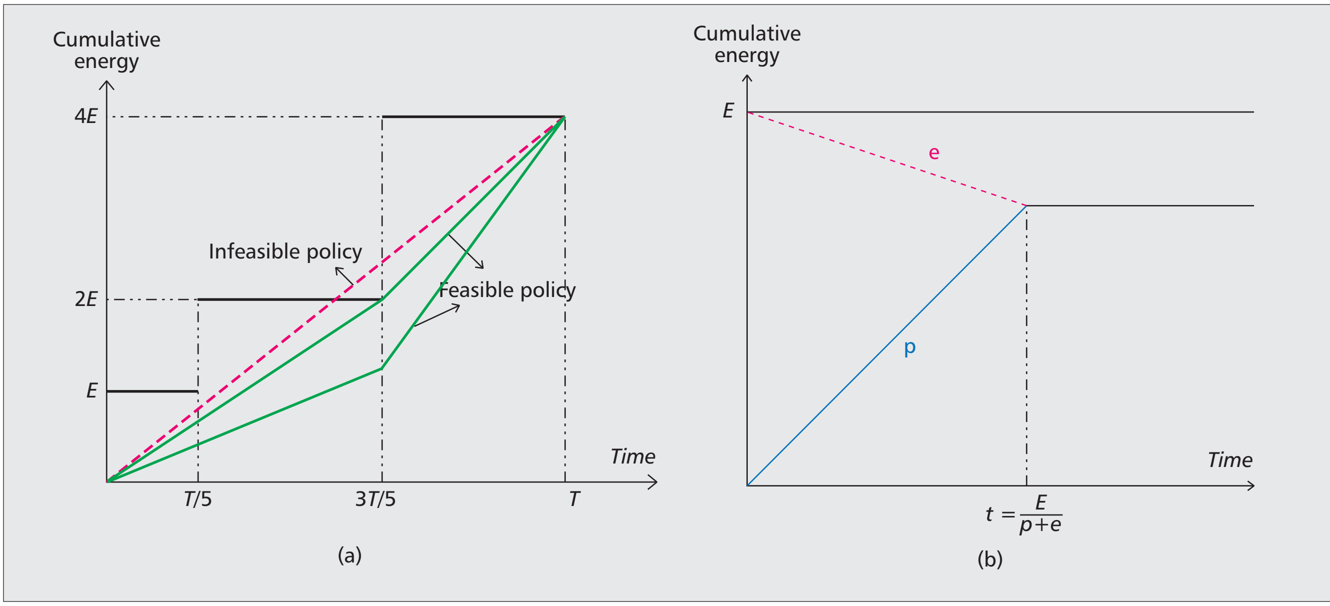

Figure 4. (a) EH profile [2] [11]; (b) EH profile with battery leakage [14].

packets arrive during the transmissions; the other scenario is when packets arrive during the transmissions. Yang and Ulukus [4] assume the energy and data buffer capacity as infinite, the CSI is perfect, and all the energy is used for transmission. There are three very important lemmas in their article. The first is that under the optimal policy, the transmit power/rate increase monotonically. The second is that the transmission power/rate remains constant between two event epochs, where an epoch is the time between two events, such as the time between the arrival of two energy packets. The third is that the energy consumed up to a specified instant is equal to the energy harvested up to that instant, meaning that the energy is used up at time T and no energy is left. As shown in Fig. 4a, the energy consumption curve must touch the energy harvesting curve at that energy harvesting instant. These three lemmas have been proved in [4] and they can help us design the optimal policy. Also, [4] gives two algorithms to minimize the transmission completion time corresponding to the two scenarios.

The model in [4] is a very optimistic single-hop model, which is not feasible in reality. Ozel and Ulukus [12] studied the optimal problem with random energy arrivals for a classical additive white Gaussian noise (AWGN) channel condition. They provide two schemes, save-and- transmit and best-effort-transmit, to achieve the optimal power management for maximizing average throughput. Meanwhile, Ozel and Tutuncuoglu [5] have proposed an algorithm called the *directional water-filling* algorithm that takes both the CSI and energy buffer capacity into account, meaning that the transmitter has a limited energy buffer capacity and communication is over a wireless fading channel. They consider two optimization problems. One is to maximize the data transmitted B by a deadline T; the other is to minimize the transmission completion time T by which the data B is completed. The *water-filling* algorithm adapts the allocation of transmission power according to the channel condition, where more power is allocated to the better channels, and poorer channels get less power in order to maximize the transmission rate. The transmitter must know the CSI to implement the water-filling algorithm. The *directional water-filling* algorithm in EH communications system is somewhat different from the water-filling algorithm because of the energy causality constraint. The power that is allocated can only transfer from left to right, which means energy transfer from past to future, because the energy we harvest in the future can not be used in the past. This is called a *right permeable tap* [5].

Although Ozel and Tutuncuoglu [5] considered CSI, they assumed the transmitter has perfect CSI, which is not practical in reality. Luo *et al.* [11] considered the optimal pilot symbol placement and power for EH communications systems. The training period and training power were optimized to obtain accurate CSI, resulting in very different solutions compared to the non-EH systems.

The solutions to maximize the data transmitted B by a deadline T and to minimize the time T by which the transmission of data B is completed are closely related, which means the two optimization problems yield identical power allocation policies, as was proven in [13]. Kaya and Aylin [13] also considered the optimal transmission policies with battery limitations, and put forward *Throughput Maximizing* and *Transmission Completion Time Minimization* algorithms to solve the two problems.

As mentioned in [2], with microelectronic systems becoming smaller and less energy demanding, the transmission energy dominates energy consumption with small transceivers. Many studies assume that all the harvested energy is only used for transmission, and the energy required for processing is not considered. Actually, the wireless systems also have processing energy cost and Orhan *et al.* [6] considered the energy consumed by both the data transmission and the processing circuitry. A *directional glue pouring* algorithm is described to compute the optimal

Model	Parameter	Scenario	Purpose	Contribution/conclusion
Yang & Ulukus [4]	Single-hop, infinite energy capacity, perfect CSI	One scenario is that all data arrived before transmission and no packets arrived during transmission, the other is that data packets may arrive during transmission	Minimize the transmission completion time	Three algorithms to minimize the transmission completion time
Ozel *et al.* [5]	Single-hop, finite energy capacity, fading wireless channel	Channel condition may change during the transmission interval	Maximize the transmitted data by a deadline and minimize the transmission completion time	A *directional water-filling* algorithm is proposed to solve the two problems
Tutuncuoglu & Yener [13]	Single-hop, finite energy capacity, AWGN channel	Sufficient amount of data is available at the beginning of data transmission	Maximize the transmitted data by a deadline and minimize the transmission completion time	*Max* algorithm and *Mini* algorithm. Maximizing the transmitted data is equivalent to minimizing the completion time
Devillers & Gunduz [6]	Single-hop, finite energy capacity, battery leakage	Single energy packet and *N* energy packet	Maximize the transmitted data by a deadline	An algorithm to maximize the transmitted data under a battery leakage condition
Orhan, Gunduz & Erkip [6]	Single-hop, finite energy capacity, fading wireless channel, processing cost	Sufficient amount of data is available at the beginning of data transmission	Maximize the transmitted data by a deadline	A *directional glue pouring* algorithm is proposed to get the optimal policy
Luo, Zhang & Letaief [8]	Two-hop, non-EH relay node, fading wireless channel	Half-duplex, sufficient amount of data is available at the source	Maximize the transmitted data by a deadline	Modified the *directional water-filling* algorithm to maximize the throughput
Gunduz & Devillers [9]	Two-hop, EH relay node, AWGN channel	Both half-duplex and full-duplex, sufficient amount of data at the source	Maximize the transmitted data by a deadline	Divide a two-hop process into two single-hop processes and use the *Max* algorithm

Table 2. Comparison of different optimal policies.

policy with processing energy cost for communication over a fading channel.

In Bertrand and Deniz [14], an EH communications system with battery leakage was proposed. The energy stored in the battery is assumed to leak at a constant finite rate, and no energy leaks when the battery is empty. The model is shown in Fig. 4b, where the red thin dashed line is the energy leaked from the battery at a constant power e, and the blue thin solid line is the energy used for transmission at a constant power p. Bertrand and Deniz [14] provided the optimal EH transmission algorithm with battery leakage.

As mentioned above, energy overflows from the battery may result in a suboptimal policy. Maria and Miquel [7] considered this problem, and a QoS constraint was put forward. A minimum data departure $B_{qos}(t)$ was defined as the smallest amount of data that must be transmitted at time T to satisfy the QoS constraint, and it can prevent battery overflows when no data is waiting for transmission.

Two-Hop Model

Many scenarios for traditional communications require two-hop or multi-hop transmission. For example, in wireless sensor networks, many nodes must use multiple hops to transmit their data to a sink node. Similarly, in EH communication systems, we require two-hop or multi-hop transmission. Due to the differences between EH systems and traditional communication systems, we need to restudy the optimal policy. Recently, many studies have focused on two-hop EH communication systems, i.e. there is a relay node between the source and destination nodes, where the source node is an EH node and the relay node may be either an EH node or battery-operated equipment.

Yaming *et al.* [8] considered an EH source and a non-EH half-duplex relay node, which means the relay node cannot harvest energy from the ambient environment and the relay node cannot receive and forward the data at the same time. The directional water-filling algorithm for single-hop EH communications system mentioned above was applied in designing the throughput maximization policy for two-hop EH communications systems. The optimal solution was obtained according to a temporary solution, and an improved directional water-filling algorithm was proposed in [8].

Orhan and Erkip [15] also considered the half-duplex optimization problem but with an

The standardization of energy harvesting communications is necessary. Either EH devices or EH communications protocols need to be standardized to assure the compatibility of different EH devices from different vendors, and for the convenience of network management.

EH relay node, and the optimal policies were studied to maximize data transmitted to the destination by a deadline T. In Deniz and Bertrand [9], both full-duplex and half-duplex communication with an EH relay node were considered. They divided a two-hop communication process into two single-hop communication processes. That is to say, with the optimal transmission schedule, the source transmits an amount of data using all its energy first, and then the relay forwards all the data received from the source to the destination by using some optimal single-hop policies as mentioned above, which have been proved in [9].

Guideline for Optimal Policy

Although both the single-hop and two-hop models are simplified scenarios, they admit analytical solutions and guidelines for designing more complicated EH communications systems. Here we conclude with some guidelines from the literature that can provide useful design insights.

For all the EH communication models:

- The optimal power management policy maintains a constant transmit power in each event epoch unless there is a new energy arrival or the channel state changes. As shown in Fig. 4a, the feasible line can only change at the corner of the EH profile.
- All energy is used up by the deadline T, i.e. the total consumed energy is equal to total harvested energy by the deadline T; otherwise it may result in suboptimal policy.
- In an optimal transmission policy, the transmit power/rate should increase monotonically in time.
- The optimal policies should follow the two causality constraints, and a battery overflow may only occur when there is no data to be transmitted.

For two-hop EH communication models:

- The source node and the relay node batteries cannot be empty simultaneously at a given time; also either source node or relay node transmits at a given time, which means they can never be silent at the same time.
- The source node transmits first and then the relay node forwards in the rest of the time, and the source and relay nodes transmit the same amount of data by the deadline in order to prevent data loss.

Table 2 compares the different optimal policies.

Research Challenges and Directions in Energy Harvesting Communications

EH communications still has some callenges to reach, and we believe that the following research directions require more attention.

Realistic Systems

The models we have studied for both offline and online energy management are very optimistic. The capacities of the battery and the data buffer capacity are assumed infinite, and the channel condition is either perfect or there is perfect CSI at the transmitter. Moreover, the energy is only used for data transmission, and other energy consuming processes in the devices are ignored, which is unrealistic in practice. When the battery capacity is much larger than the harvested energy, we can assume the battery capacity is sufficient and regard it as infinite. However, in reality wireless devices may not have large-capacity batteries due to cost constraints, and we can harvest more energy with the development of energy harvesting technology so that we have to consider the problem of the battery capacity, which is the same as the data capacity. Future work should consider battery and data capacity, processing cost, and imperfect CSI at the transmitter to model realistic EH communications environments.

Network Architecture for Energy Harvesting Communications

Existing studies have considered single-hop and two-hop EH communications systems. A realistic wireless communication network may consist of many nodes. Future studies may consider the multi-hop model shown in Fig. 3c, i.e. EH network architectures and optimization problems. Moreover, in addition to the wireless network nodes, the base stations may also use EH equipment. An interesting direction of research is to build an optimal or sustainable energy harvesting network architecture.

Algorithms and Protocols

There are a variety of protocols and routing algorithms in wireless sensor networks, and many of them consider the energy management problem. The optimal policies reviewed in this article are simple, optimistic, point-to-point algorithms. Hence, algorithms and protocols for EH communications are needed that are chosen according to the type of energy harvesting network architecture, such as a broadcast protocol for point to multi-point, and optimal routing algorithms based on multi-hop architectures. Moreover, the security of communications with EH may also be considered, which may be more complex and require more careful attention than their non-EH counterparts.

Standardization

Most technologies and solutions for EH communications are still not mature. Thus, the standardization of energy harvesting communications is necessary. Both the EH devices and the EH communications protocols need to be standardized to assure the compatibility of different EH devices from different vendors, and for the convenience of network management.

Conclusions

This article has surveyed existing EH communications technologies and theories. Our focus has been on offline optimal policies to provide for the best management of EH power, and we compared different kinds of optimization schemes. Some guidelines have been given for designing an optimal EH policy. Finally, we discussed the challenges and directions for future energy harvesting communications, which can help us design better EH communications systems.

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References

[1] R. V. Prasad *et al.*, "Reincarnation in the Ambiance: Devices and Networks with Energy Harvesting," *IEEE Commun. Surveys & Tutorials*, vol. 16, no. 1, 1st Quarter, 2014, pp. 195–213.

[2] E. Gelenbe *et al.*, "Energy Harvesting Communication Networks: Optimization and Demonstration (The E-CROPS Project)," *Green ICT (TIWDC), 2013 24th Tyrrhenian Int'l. Wksp. Digital Commun.*, Sept. 2013, pp. 1–6.

[3] D. Gunduz *et al.*, "Designing Intelligent Energy Harvesting Communication Systems," *IEEE Commun. Mag.*, vol. 52, no. 1, Jan. 2014, pp. 210–16.

[4] J. Yang and S. Ulukus, "Optimal Packet Scheduling in an Energy Harvesting Communication System," *IEEE Trans. Commun.*, vol. 60, no. 1, Jan. 2012, pp. 220–30.

[5] O. Ozel *et al.*, "Transmission with Energy Harvesting Nodes in Fading Wireless Channels: Optimal Policies," *IEEE JSAC*, vol. 29, no. 8, Sept. 2011, pp. 1732–43.

[6] O. Orhan, D. Gunduz, and E. Erkip, "Throughput Maximization for an Energy Harvesting Communication System with Processing Cost," *2012 IEEE Info. Theory Wksp. (ITW)*, Sept. 2012, pp. 84–88.

[7] M. Gregori and M. Payaro, "Energy-Efficient Transmission for Wireless Energy Harvesting Nodes," *IEEE Trans. Wireless Commun.*, vol. 12, no. 3, Mar. 2013, pp. 1244–54.

[8] Y. Luo, J. Zhang, and K. B. Letaief, "Throughput Maximization for Two-Hop Energy Harvesting Communication Systems," *2013 IEEE Int'l. Conf. Commun. (ICC)*, June 2013, pp. 4180–84.

[9] D. Gunduz and B. Devillers, "Two-Hop Communication with Energy Harvesting," *2011 4th IEEE Int'l. Wksp. Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP)*, Dec. 2011, pp. 201–04.

[10] E. S. Leland, E. M. Lai, and P. K. Wright, "A Self-Powered Wireless Sensor for Indoor Environmental Monitoring," *WNCG Conf.*, 2004.

[11] Y. Luo, J. Zhang and K. B. Letaief, "Training Optimization for Energy Harvesting Communication Systems," *2012 IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2012, pp. 3365–70.

[12] O. Ozel and S. Ulukus, "Information-Theoretic Analysis of an Energy Harvesting Communication System," *2010 IEEE 21st Int'l. Symp. Personal, Indoor and Mobile Radio Communications Wksps. (PIMRC Workshops)*, Sept. 2010, pp. 330–35.

[13] K. Tutuncuoglu and A. Yener, "Optimum Transmission Policies for Battery Limited Energy Harvesting Nodes," *IEEE Trans. Wireless Commun.*, vol. 11, no. 3, Mar. 2012, pp. 1180–89.

[14] B. Devillers and D. Gunduz, "A General Framework for the Optimization of Energy Harvesting Communication Systems with Battery Imperfections," *J. Commun. and Networks*, vol. 14, no. 2, Apr. 2012, pp. 130–39.

[15] O. Orhan and E. Erkip, "Energy Harvesting Two-Hop Networks: Optimal Policies for the Multi-Energy Arrival Case," *2012 35th IEEE Sarnoff Symposium (SARNOFF)*, May 2012, pp. 1–6.

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