Energy Cooperation in Battery-Free Wireless Communications with Radio Frequency Energy Harvesting

メタデータ	言語: English 出版者: ACM 公開日: 2019-06-27 キーワード (Ja): キーワード (En): 作成者: 李, 鶴, 太田, 香, 董, 冕雄 メールアドレス: 所属:
URL	http://hdl.handle.net/10258/00009925

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Radio frequency (RF) energy harvesting techniques are becoming a potential method to power battery-free wireless networks. In RF energy harvesting communications, energy cooperation enables shaping and optimization of the energy arrivals at the energy-receiving node to improve the overall system performance. In this paper, we proposed an energy cooperation scheme that enables energy cooperation in battery-free wireless networks with RF harvesting. We first study the battery-free wireless network with RF energy harvesting then state the problem that optimizing the system performance with limited harvesting energy through new energy cooperation protocol. Finally, from the extensive simulation results, our energy cooperation protocol performs better than the original battery-free wireless network solution.

CCS Concepts: • **Networks** → **Network architectures**; **Network protocols**; **Network properties**; **Network manageability**; **Sensor networks**; • **Hardware** → **Renewable energy**;

Additional Key Words and Phrases: Batter-free networks, Energy cooperation, RF energy harvesting

ACM Reference Format:
HE LI, KAORU OTA, and MIANXIONG DONG. 2017. Energy Cooperation in Battery-Free Wireless Communications with Radio Frequency Energy Harvesting. *ACM Trans. Embedd. Comput. Syst.* 1, 1, Article 1 (January 2017), 19 pages. https://doi.org/10.1145/3141249

1 INTRODUCTION

Battery-free wireless networks avoid the battery replacement of the traditional wireless networks, which are applied for more applications, e.g., wireless sensor networks [24] [31], Internet of Things (IoT) [20] [32], and the fifth generation communication networks [1]. In battery-free wireless networks, the nodes harvest energy from the environment for the wireless communications, which can supply power infinitely [15] [33].

Recent years, radio frequency (RF) energy harvesting is playing an important role in wireless networks that wireless nodes can harvest energy from RF waves to extend network lifetime [3] [26] [19]. For battery-free wireless networks, RF harvesting is also considered as an emerging technology to maintain data communications [23]. Since RF energy sources are discontinuous distributed, some wireless nodes are hard to harvest enough energy. In general wireless networks, as the nodes in wireless networks have batteries to store energy, it

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1539-9087/2017/1-ART1 $15.00
https://doi.org/10.1145/3141249

is possible to maintain the network through careful energy management [13] [28]. However, as wireless nodes need continuous energy supplement, battery-free networks are difficult to work well on simple energy management [18].

Energy cooperation is a potential solution to enable battery-free wireless networks with RF harvesting. Because of the intermittency of Rf energy distribution, some wireless nodes will harvest more than necessary energy [10]. Energy cooperation means the wireless nodes with substantial energy can share their energy to those energy deprived nodes, which is an efficient methodology to improve the network performance of general wireless networks. As the nodes in battery-free are not able to store excessive energy, energy cooperation needs more dedicated control to improve the energy efficiency.

In this paper, we propose an energy cooperation scheme to improve the network performance of battery-free wireless networks. We first study the battery-free wireless networks with RF energy harvesting and introduce energy cooperation into the communication protocol. Then, we formulate the problem to minimize the overall latency of the given battery-free wireless network with RF energy harvesting. We solve the problem of the latency optimization with an energy cooperation protocol. We also formulate and analyze the efficiency of the energy cooperation protocol in the given battery-free wireless network. For evaluating the energy cooperation performance, we take extensive simulations and the numerical results show the network latency is decreased by our protocol.

The main contributions of this paper are summarized as follows.

- We first study the energy cooperation to optimize the network performance of battery-free wireless networks with RF energy harvesting. Since RF energy powering battery-free networking is a prospective technology, our work is the first work to optimize the network performance through energy cooperation.
- We then design the energy cooperation protocol to minimize the network latency of the battery-free wireless network. It is a challenging problem which needs to understand thoroughly the impact of energy harvesting and cooperation in the battery-free wireless network.
- We take the performance evaluation of the energy cooperation protocol with extensive simulations with settings from realistic battery-free wireless networks. We also compare our pricing strategy with the original network and the results show that our protocol decreases the network latency.

The rest of this paper is summarized as follows. Section 2 reviews the related work. Our network scenario and motivations are introduced in Section 3. Section 4 presents the problem formulation. An optimal energy cooperation protocol is proposed in Section 5. Section 6 gives the simulation results. Finally, Section 7 concludes this paper and give the future work.

2 RELATED WORK

In this section, we first introduce some main technologies of RF harvesting in battery-free wireless networks. Then, we discuss some energy cooperation strategies with RF harvesting.

2.1 RF energy harvesting in battery-free wireless networks

Some previous works focus on the design and implementation of battery-free wireless devices with RF energy harvesting. Radio frequency identification (RFID) applications are considered as an important area of battery-free devices. [25] proposed a programmable battery-free sensing and computational platform for sensor-enhanced RFID applications. They extend the maximum operational range of RFID sensing to 4.3m and provide a communication channel based on RFID reader physical layer.

Harvesting ambient RF energy is an important method for powering battery-free devices. [2] first analyzed the spectrum opportunities for harvesting energy from ambient radio waves. Through their analysis, harvesting RF energy from ambient radio waves shows acceptable efficiency for powering battery-free devices. Thus, [21] designed a battery-free device powered by harvesting RF energy from indoor WiFi access points. Even though they improved the energy harvesting efficiency, the harvested power is not enough for wireless communication.

Harvest energy from terrestrial television (TV) broadcasts is a perpetual power source for battery-free systems. [29] presented an RF energy harvesting battery-free device to harvest energy from the TV broadcast. They design a large log-periodic antenna to harvest 500-600 MHz TV signals and produce enough power for sensing and communication. From the result, the harvested power is also limited for maintaining a battery-free wireless network.

Some researchers introduce wireless communications into battery-free devices. [30] proposed a body area sensor node chip powered by both RF and thermoelectric power. In their design, the frequency-multiplying transmitter can provide a maximum data rate of 200kbps. However, the authors only implemented a single node system and the communication range is limited by harvesting ambient RF energy.

Thus, as a wireless network needs higher energy supplement than ambient RF energy harvesting, energy transmitters or chargers are deployed for energy transferring. Previous studies proposed efficient solutions for wireless rechargeable sensor networks [6] [7] [11] [4] [8]. Although these works focus on batteries charging on wireless nodes, RF energy transferring or charging shows enough capacity for powering battery-free systems. Therefore, [17] studied a battery-free wireless sensor network powered by RF energy chargers. They present a well-designed RF energy charger placement to minimize the number of chargers. Their research shows that powering battery-free wireless networks through additional RF chargers or energy transmitters is an efficient solution.

2.2 Energy cooperation through RF energy harvesting

Energy cooperation is an efficient methodology to improve the device energy supplement through RF energy harvesting. [9] first studied energy cooperation in the wireless communications then proposed a generalized two-dimensional directional water-filling algorithm to obtain the boundary of the energy capacity regions. Based on this research, [27] presented a class of optimal energy cooperation policies in a multi-source relay channel model with energy harvesting transmitters. They presented a unidirectional energy cooperation scheme which is more appropriate for the practical scenarios. The energy cooperation shows enough efficiency on energy transferring.

Energy cooperation is also able to improve the network performance. [12] studied the classic three-node Gaussian relay channel with decode-and-forward relaying. For maximizing the throughput, they proposed a two-stage power allocation algorithm to obtain the optimal solution. However, the three-node network is not so practical for general wireless networks.

More studies focus on energy cooperation in more complex networks. For example, [5] proposed an energy cooperation model between base stations in cellular networks. They design an optimal energy cooperation policy for minimizing the energy consumption of base stations. [14] studied an emerging wireless powered communication network which is similar to a cellular network. They proposed an optimal strategy to improve the network performance through the energy cooperation.

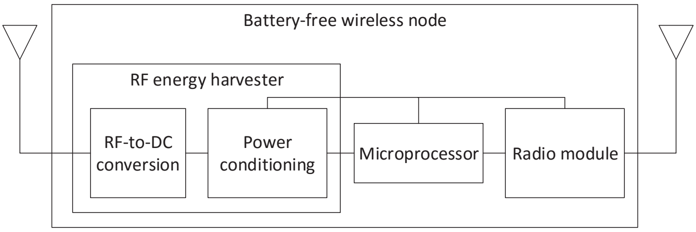


Fig. 1. Battery-free wireless node with RF energy harvesting

Furthermore, as the frequency for energy transferring is usually different from data transmission for minimum interference, some researchers proposed energy cooperation which is independent of data communications. [34] proposed an energy and information cooperation scheme in RF powered cognitive radio networks. A primary network can provide both information and energy to a secondary network with RF energy harvesting, and the secondary network assists the primary transmission. In their network settings, the RF energy transferring and the data transmission is divided into two distinguished levels. From their simulation results, the energy and information cooperation improves the both primary and secondary system.

From discussed works, the energy cooperation shows promising efficiency in RF energy harvesting systems. Therefore, in this paper, we try to introduce the energy cooperation into the battery-free wireless network with RF energy harvesting to improve the overall network performance.

3 BACKGROUND AND MOTIVATION

In this section, we first introduce the scenario of a battery-free wireless network with RF energy harvesting. Then, we discuss the motivations on the energy cooperation to improve the network performance.

3.1 Battery-free wireless networks with RF energy harvesting

Because of the lower cost of maintenance and materials, battery-free devices are applied to build wireless networks, such as wireless sensor networks and Internet of Things. For powering battery-free wireless networks, RF energy harvesting shows better efficiency and available than other solutions such as solar radiation, the wind and kinetic, as battery-free devices can harvest RF energy in communications and the ambient RF energy is almost unaffected by environment.

We first discuss a typical structure of battery-free device with RF energy harvesting shown in Fig. 1. A battery-free device will have an independent antenna for energy harvesting and another one for communications. As the limited energy supplement, it is hard to apply the complex design that harvesting energy and communicating through a single antenna. The RF energy harvester will transfer the RF energy to DC power. The power conditioning in harvester stabilizes the power voltage for the workload. The rest parts are similar to an ordinary node in wireless communications, which includes a microprocessor and a radio module.

For powering these wireless nodes, there are two solutions. One solution is harvesting energy from ambient RF sources such as TV broadcast transmitters, cellular base stations, and

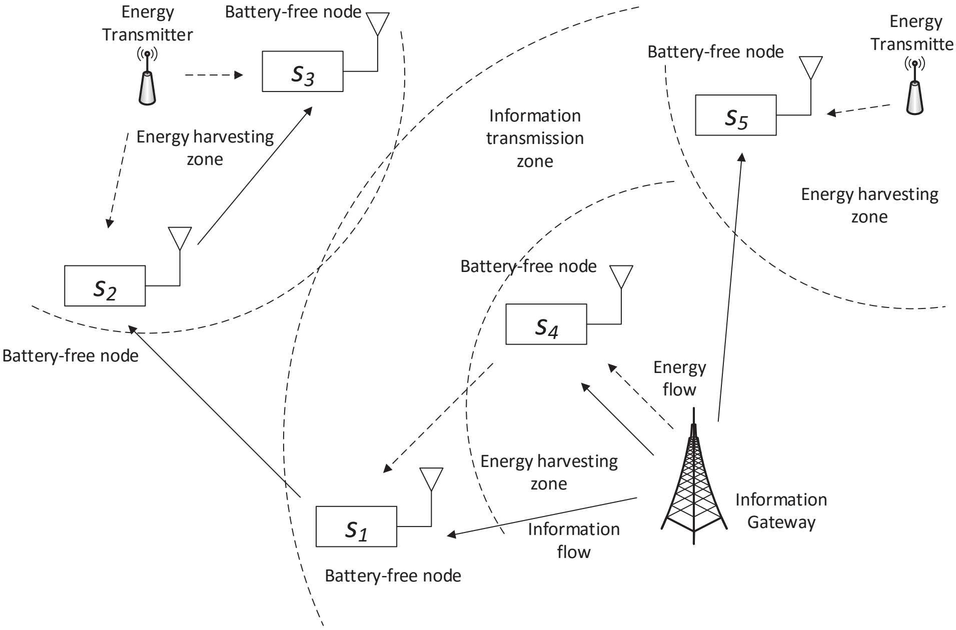


Fig. 2. Energy cooperation with RF energy harvesting

AM/FM radio transmitters. Ambient RF sources can cover wide areas and provide stable energy supplement. However, for a single node, harvested energy is limited by the ambient RF sources. Moreover, as the ambient RF sources may operate on different frequencies, it needs different antennas to harvest energy.

Direct RF energy transferring can be used for powering battery-free devices out of the ambient RF energy coverage areas. In direct RF energy transferring, energy transmitters are set in the wireless network area and transfer energy to wireless nodes through a specific frequency. For example, 915 MHz is a reserved frequency for wireless energy transferring and applied in some commercial solutions. Direct RF energy transferring provides high efficiency through directional antennas in a short distance while the energy is significantly attenuated by the distance. Moreover, the devices outside of the antenna beam are not able to harvest energy from the transmitter. Energy cooperation seems a potential solution to improve the efficiency

3.2 Energy cooperation scenario

In a battery-free network, as the energy is not distributed evenly, wireless nodes can cooperate with each other for energy transferring. As shown in Fig. 2, we use an example to describe the basic scenario of energy cooperation in a battery free network. In this energy cooperation scenario, there are battery-free wireless nodes, information gateway, and energy transmitter. We use s_1, s_2, s_3, s_4, and s_5 to denote the wireless nodes. The information gateway transmits information to nodes in the information transmission zone and powers nodes in the energy harvesting zone while energy transmitters power the nearby nodes.

As the limited range of information transmission, wireless nodes will cooperate into an ad-hoc network to cover the nodes outside of the transmission range. For example, as node s_2 and s_3 are out of the information transmission zone, node s_1 first transmit data to s_2 then s_2 transmit data to s_3. For energy harvesting, as the energy harvesting zone is much smaller than information transmission zone, additional energy transmitters are needed to cover the nodes without energy supplement. In the example, node s_2, s_3, and s_5 harvest energy from energy transmitters. However, for power node s_1, node s_4 have to transfer extra energy through RF antenna, which means energy cooperation.

In this case, there are several problems. First, as the battery-free design of wireless nodes, it is not allowed to buffer energy in batteries. Second, as the limited transmit power, it will need multiple nodes to power a single node. Third, the network performance is limited by the transmit power. As a result, we propose a solution to optimize the battery-free network through the energy cooperation protocol.

4 PROBLEM STATEMENT

In this section, we first model the energy cooperation in battery-free wireless networks with RF energy harvesting then state the problem of the energy cooperation strategy to minimize the network latency with a given energy supplement. We list all notations in the energy cooperation in a battery-free wireless network with RF energy harvesting in Table 1. We assume the frequencies of energy harvesting and information communications are distinct with negligible interference. Each battery node has three antennas, in which one is for energy harvesting, one is for information communication, and one is for energy cooperation. We also assume the network connectivity and packet routing are not influenced by additional energy cooperation.

As shown in Fig. 2, we use S to denote the set of battery-free wireless nodes and s_i ($i \in [1, |S|]$) to denote a node in set S. For node s_i, let H_i denote the harvesting antenna gain and R_i denote the communication antenna gain. For the information gateway, we use P_g to denote the transmit power for information transmission, G_g to denote the gain of the transmit antenna, and r_i to denote the distance between node s_i and information gateway. Let λ_c denote the information transmission frequency. Therefore, for each node s_i, we use P_i^g to denote the received power from the gateway, given by

$$P_i^g = P_g \cdot \frac{G_g \cdot R_i \cdot {\lambda_c}^2}{(4 \cdot \pi \cdot r_i)^2 \cdot L} \tag{1}$$

where L is the path loss factor.

For the energy harvesting, we use B to denote the set of energy transmitters and b_j ($j \in [1, |B|]$) to denote a transmitter in set B. For energy transmitter b_j, let P_j denote the transmit power for energy harvesting, G_j to denote the antenna gain, and r_{ij} to denote the distance from node s_i. Let λ_e denote the energy harvesting frequency. Therefore, for each node s_i, we use P_{ij}^b to denote the received power from energy transmitter b_j to node s_i, give by

$$P_{ij}^b = P_j \cdot \frac{G_j \cdot H_i \cdot {\lambda_e}^2}{(4 \cdot \pi \cdot r_{ij})^2 \cdot L} \tag{2}$$

Then, we study the original network performance without energy cooperation. We first study the transmit power of a single node. Let P_i^p denote the power consumption of the chips and related circuit in node s_i. Let η_i denote the energy efficiency from the harvesting

Table 1. Notations for the problem statement

Notation	
S	Set of wireless nodes
s_i	One wireless node in S
H_i	Harvesting antenna gain of node s_i
R_i	Communication antenna gain of node s_i
C_k	Cooperation antenna gain of node s_k
P_g	Transmit power of the information gateway
G_g	Transmit antenna gain of the information gateway
r_i	Distance from node s_i to the information gateway
λ_c	Communication frequency
P_i^g	Received power from the information gateway to node s_i
L	Path loss factor
B	Set of energy transmitters
b_j	One transmitter in set B
P_j	Transmit power of transmitter b_j
G_j	Antenna gain of transmitter b_j
r_{ij}	Distance between node s_i and transmitter b_j
P_{ij}^b	Received power from transmitter b_j to node s_i
η_i	Harvesting efficiency of node s_i
P_i^p	Power consumption of the chips and related circuit in node s_i
P_i^e	Output power for communications of node s_i
P_{ik}^r	Received power from node s_k to s_i
E_b	Energy per bit
$N_0/2$	noise power spectral density
P_x	Required BER
P_{ik}^x	BER for node s_i receiving data from s_k
P_f	Fading margin
N_i	Noise power of node s_i
N_i^f	Noise figure of node s_i
B_i^w	Channel bandwidth of node s_i
$\mathcal{K}$	Boltzmann's constant
T	Temperature
P_i^h	Output power for energy cooperation of node s_i
l_p	Packet size
R_i	Forwarding path from the information gateway to node s_i
d_i	Transmission latency from the information gateway to node s_i

antenna to the node s_i. We use P_i^e to denote the input energy of the node s_i as

$$P_i^e = \sum_{j=1}^{|B|} P_{ij}^b \cdot \eta_i - P_i^p \tag{3}$$

For the communication between two nodes, let P^r_{ik} denote the input energy of node s_i received from node s_k, given by

$$P^r_{ik} = P^e_k \cdot \frac{R_k \cdot R_i \cdot {\lambda_c}^2}{(4 \cdot \pi \cdot r_{ik})^2 \cdot L} \tag{4}$$

where r_{ik} is the distance between node s_i and s_k.

Then, we study the data rate with the input energy. As we assume the network uses quadrature phase-shift keying (QPSK) modulation, let P^x_{ik} denote the bit error rate (BER) for node s_i receiving signal from node s_k, given by

$$P^x_{ik} = Q(\sqrt{\frac{2 \cdot E_b}{N_0}}) \tag{5}$$

where $Q(\cdot)$ is a scaled form of the complementary Gaussian error function, E_b is energy per bit, and $N_0/2$ is the noise power spectral density.

As a low BER is required for the data communications, let P_x denote the required BER and $P^x_{ik} \leq P_x$ for node s_i receives data from node s_k. Now we study the relationship between BER and received power for node s_i receives data from node s_k as

$$\frac{P^r_{ik}}{N_i \cdot P_f} = \frac{E_b}{N_0} \cdot \frac{fb_{ik}}{B^w_i} \tag{6}$$

where P_f is the fading margin, N_i is the noise power of node s_i, fb_{ik} is the bit rate of the data transmission from node s_i to s_k, and B^w_i is the channel bandwidth of node i.

As $N_i = \mathcal{K} \cdot T \cdot B^w_i + N^f_i$ where $\mathcal{K}$ is Boltzmann's constant, T is temperature, N^f_i is the noise figure of node s_i, the value of fb_{ik} is sufficient as

$$fb_{ik} \leq \frac{2 \cdot B^w_i \cdot P^r_{ik}}{(Q^{-1}(P_x))^2 \cdot (\mathcal{K} \cdot T \cdot B^w_i + N^f_i) \cdot P_f} \tag{7}$$

Similarly, let fb_i denote the bit rate from the information gateway to node s_i, give by

$$fb_i \leq \frac{2 \cdot B^w_i \cdot P^g_i}{(Q^{-1}(P_x))^2 \cdot (\mathcal{K} \cdot T \cdot B^w_i + N^f_i) \cdot P_f} \tag{8}$$

Now, with the harvested energy from cooperation, we study the data rate from node s_i to a given node s_k.

Thus, we study the energy cooperation in this network. We use P^h_i to denote the power for energy cooperation. With P^h_i, let P^t_i denote the transmit power of node s_i, given by

$$P^t_i = P^e_i - P^h_i \tag{9}$$

We use C_k to denote the antenna gain for energy cooperation of node s_k. For node s_i, let P^h_{ik} denote the harvested energy from node k with energy cooperation, give by

$$P^h_{ik} = P^h_i \cdot \frac{H_i \cdot C_k \cdot {\lambda_e}^2}{(4 \cdot \pi \cdot r_{ik})^2 \cdot L}. \tag{10}$$

Therefore, with energy cooperation, the overall input energy P^e_i is calculate as

$$P^e_i = (\sum_{j=1}^{|B|} P^b_{ij} + \sum_{k=1}^{|S|} P^h_{ik}) \cdot \eta_i - P^h_i - P^p_i \tag{11}$$

where $k \in [1, |S|]$.

We study the transmission latency of the battery-free wireless network with energy cooperation. In the energy cooperation scenario, each node transmits the extra energy in energy

ALGORITHM 1: Energy cooperation protocol

```
Input: Node $s_i$
Output: Output power $P_i^h$ for energy cooperation
repeat
    if Receive cooperation request then
        $P_i^h \leftarrow P_i^e$;
    end
    repeat
        for packet $p_{ik}$ in transmit queue do
            while $P_i^h > 0$ and $fb_{ik} \leq fb_{max}$ do
                $P_i^h \leftarrow P_i^h - \Delta P$;
            end
            Send packet $p_{ik}$;
        end
    until Transmit queue is empty or Channel is idle;
    repeat
        Put input packet $p_{ik}$ into transmit queue
    until Input packet is empty;
until Voltage < Normal voltage;
repeat
    repeat
        Multicast cooperation request;
    until Voltage < Minimal voltage;
    Sleep;
until Voltage > Normal voltage;
```

harvesting to others, in which the energy level for communications is not changed. Thus, the forwarding path in energy cooperation remains the same with general battery-free communications. Let R_i denote the forwarding path from the information gateway to node s_i. Therefore, we use d_i to denote the latency of transmitting one packet from the information gateway to node s_i, given by

$$d_i = \frac{l_p}{fb_1} + \sum_{k=2}^{|R_i|} \frac{l_p}{fb_{k(k+1)}} \tag{12}$$

where $s_{k,k=1,2,\ldots,|R_i|}$ is the nodes in forwarding path R_i and l_p is the packet size.

The problem of energy cooperation in the battery-free wireless network with RF energy harvesting (ECBWN): given a battery-free wireless network consisting of a set of battery-free wireless nodes, an information gateway, and a set of energy transmitters, the ECBWN problem attempts to adjust the output energy for energy cooperation of each battery-free wireless node to minimum the transmission latency.

5 ENERGY COOPERATION PROTOCOL

In this section, we propose the energy cooperation protocol to solve the ECBWN problem. We first describe the design of our protocol then analyze the performance in a given battery-free wireless network.

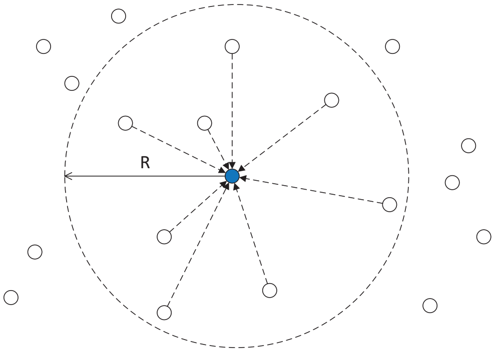


Fig. 3. Energy cooperation for a single node

5.1 Protocol design

As shown in Algorithm 1, we design a protocol for energy cooperation in battery-free communications. First, if the node receives one or more energy cooperation requests, the protocol sets the output power for energy cooperation equal to the input power. We first set output power P_i^h for energy cooperation to input energy P_i^e. Then, the node will sleep until a packet comes.

When the node receives a packet, the node will put the received packet into the transmit queue for the future forwarding. If the communication protocol and RF module are duplex, the node will send the packet to the transmit queue simultaneously. For half-duplex networks, the node will wait all packets are received. In our scenario, we assume all communications between battery-free nodes are full duplex.

For transmitting packet, as the node needs enough transmit energy, output energy P_i^h is decreased and more energy is reserved for transmitting packets. As input energy P_i^e is dynamically varying with the energy cooperation scheme, the node will adjust P_i^h through an iterative calculation. For multiple nodes sending data or harvesting energy, we assume there is a simple collision avoidance mechanism in each battery node. Thus, in our protocol, the node will stop sending packets when the channel is not idle.

The minimal voltage is the voltage for the radio module send packets with the lowest power. The normal voltage is the voltage for the radio module and microprocessor working in the normal status. If the voltage is lower than normal voltage, the node will multicast an energy request with the lowest power. If the voltage becomes lower than minimal voltage, the node will sleep until the voltage recovery.

5.2 Performance analysis

Then, we try to analyze the performance of the energy cooperation protocol. We first assume all nodes are uniformly distributed in the network area and all nodes have the same parameters, which means $H_1 = H_2 = ... = H_{|S|} = H$, $P_1^p = P_2^p = ... = P_{|S|}^p = P^p$, $C_1 = C_2 = ... = C_{|S|} = C$, and $\eta_1 = \eta_2 = ...\eta_{|S|} = \eta$. We use $\mathbb{S}$ to denote the size of the entire network area. As shown in Fig. 3, a single node can harvest energy from the nearby nodes. We use r^h to denote the maximum range of energy harvesting in cooperation. Thus, the area for energy harvesting or node s_i is $\pi \cdot (r^h)^2$. Let S_i^h denote the node in the energy harvesting area of node s_i. Let $E(|S_i^h|)$ denote expected number of node in S_i^h, given by

$$E(|S_i^h|) = \frac{\pi \cdot (r^h)^2}{\mathbb{S}} \cdot |S|. \tag{13}$$

We use $E(P_{r^h}^h)$ to denote the expected harvested energy of all nodes in energy cooperation and $E(P_{r^h j}^h)$ to denote expected energy that the nodes in the circle harvest from energy transmitter b_j. Expected harvested energy $E(P_{r^h}^h)$ can ba calculated as

$$E(P_{r^h}^h) \geq \sum_{j=1}^{|B|} E(P_{r^h j}^h) \tag{14}$$

We first study the case that only node s_i is transmitting data while other nodes in the circle area are transferring energy for cooperation. Thus, as we assume the nodes in the circle area can harvested more power than inherent energy consumption, expected harvested energy $E(P_{r^h}^h)$ is calculated as

$$E(P_{r^h}^h) \approx P_j \cdot \frac{G_j \cdot H^2 \cdot C \cdot \lambda_e^4 \cdot \eta^2 \cdot |S|}{64 \cdot \pi^4 \cdot \mathbb{S}} \cdot \int_0^{r^h} \int_0^{r^h} \frac{1}{(x^2 + y^2) \cdot ((r_{ij} - x)^2 + y^2)} \mathrm{d}x\mathrm{d}y \tag{15}$$

We also assume the $r^h \ll r_{ij}$ since the transferred energy from battery-free nodes is much smaller than the energy transmitter. Therefore, we can get the expected harvested energy $E(P_{r^h}^h)$ as

$$E(P_{r^h}^h) \approx P_j \cdot \frac{G_j \cdot H^2 \cdot C \cdot \lambda_e^4 \cdot \eta^2 \cdot |S|}{32 \cdot \pi^3 \cdot r_{ij}^2 \cdot \mathbb{S}} \cdot \log r^h \tag{16}$$

Then, with expected harvested energy from energy cooperation, let fb_{ik}^* denote the maximum data rate for node s_i transferring data to a given node k, given by

$$fb_{ik}^* = \frac{2 \cdot B_i^w \cdot P_{ik}^{r*}}{(Q^{-1}(P_x))^2 \cdot (\mathcal{K} \cdot T \cdot B_i^w + N_i^f) \cdot P_f} \tag{17}$$

where P_{ik}^{r*} is the new input energy for data communications.

Therefore, let $\mathcal{A}_i$ denote the expected performance ratio of data rate between energy cooperation and original protocols when only node s_i is transferring data, given by

$$\mathcal{A}_i = \frac{fb_{ik}^*}{fb_{ik}} = \frac{P_{ik}^{r*}}{P_{ik}^r} = \frac{P_{ij}^{b*}}{P_{ij}^b} = \frac{P_{ij}^b + E(P_{r^h}^h)}{P_{ij}^b} \geq 1 + \frac{H \cdot C \cdot \eta^2 \cdot |S| \cdot \log r^h}{2 \cdot \pi \cdot \mathbb{S}} \tag{18}$$

where P_{ik}^{r*} is the received energy of node s_k during data communications with node s_i through energy cooperation protocol.

Let J denote the expected number of hops for data forwarding. As the transmit power of the information gateway is much higher than nodes, the latency in the first hop is much smaller than latency in other hops. Let $\mathcal{A}$ denote the expected performance ratio of latency between energy cooperation and original protocols when only one forwarding path is transferring data, given by:

$$\mathcal{A} \leq \frac{2 \cdot \pi \cdot \mathbb{S}}{2 \cdot \pi \cdot \mathbb{S} + H \cdot C \cdot \eta^2 \cdot |S| \cdot \log r^h}. \tag{19}$$

Now, we study our protocol performance with more throughput in the given network. We assume r^h is smaller than the distance in one hop and the information gateway only communicates with one single node. It is easy to know that for a given node, the expected ratio of the time for data transmission in entire period is $\frac{1}{J}$. Therefore, in a given time slot, only $\frac{1}{J}$ nodes are transmitting data and $\frac{J-1}{J}$ nodes are waiting or receiving data. As a result, let $\mathcal{B}_i$ denote the expected performance ratio between energy cooperation and original protocols of node s_i with higher throughput, given by

$$\mathcal{B}_i \geq 1 + \frac{H \cdot C \cdot \eta^2 \cdot |S| \cdot (J-1) \cdot \log r^h}{2 \cdot \pi \cdot J \cdot \mathbb{S}}. \tag{20}$$

Finally, Let $\mathcal{B}$ denote the expected performance ratio of latency between energy cooperation and original protocols, given by:

$$\mathcal{B} \leq \frac{2 \cdot \pi \cdot J \cdot \mathbb{S}}{2 \cdot \pi \cdot J \cdot \mathbb{S} + H \cdot C \cdot \eta^2 \cdot |S| \cdot (J-1) \cdot \log r^h}. \tag{21}$$

6 PERFORMANCE EVALUATION

In this section, we first describe the simulation settings then provide simulation results to evaluate the performance of our proposed energy cooperation protocol in the battery-free wireless network with RF energy harvesting.

6.1 Simulation settings

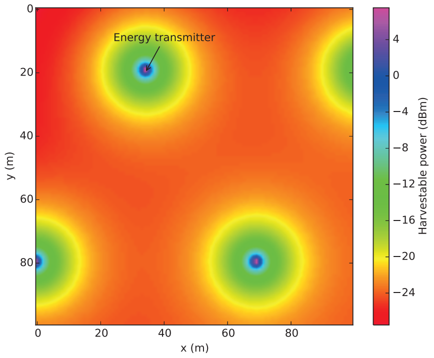
To evaluate the performance in general cases, we generate random networks and compare the network latency of our protocol to the original network.

In our simulation, we run a python 2.7 script with the networkx library 1.6 on a desktop computer. After surveying many existing battery-free or RF harvesting systems, we select the parameters of the simulation from some practical works. We set the antenna gain of the energy transmitter is 15dBi on 915MHz, which is a common value of commercial products. The antenna gain for RF energy harvesting is set to 7.5dBi from [16]. We assume the gain antenna for energy cooperation is a replicate of the energy harvesting antenna. From some previous works, as the gain of communication antenna is usually very small with lower energy consumption, we set it to 0dBi in our simulations. We choose a 100×100 area for all simulations and the default number of nodes is set to 200. The default output power of energy transmitters is set to 30dBm or 1000mW. We put 4 energy transmitters in the area for powering all battery-free nodes. The information gateway is put in the center of the area. In the data communication, the information gateway sends packets to each node and at any time, we first assume there is only one packet is transmitted in the network. We also test the network latency when two packets are transmitted in the network. From the standard ARIB STD-T66 [22], we set the antenna gain of the information gateway is 2.14dBi and transmit power is 24dBm.

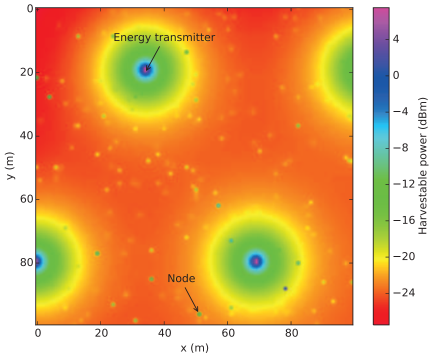
As there are no other energy cooperation methods for battery-free networks, we test the performance of an original mode without energy cooperation for comparison.

6.2 Numerical results

We first study the harvestable energy for each node. As shown in figure 4(a), we use four energy transmitters in 100×100m area and calculate the energy that a node can harvest in every position. We use different colors to show the value of harvestable energy. As the transferred power is quadratic attenuated by distance, the harvestable energy is significantly decreased below -20dBm when the distance from the transmitter becomes 10 meters. From the result show in Fig. 4(b), although each node only covers a small area, the energy cooperation protocol improves the harvestable energy even in the place far from the energy transmitters.



(a) Original



(b) Energy cooperation

Fig. 4. Harvestable RF energy heatmap in the network area

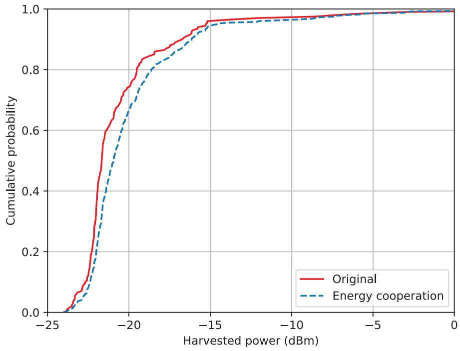


Fig. 5. Cumulative probability of each node harvested power

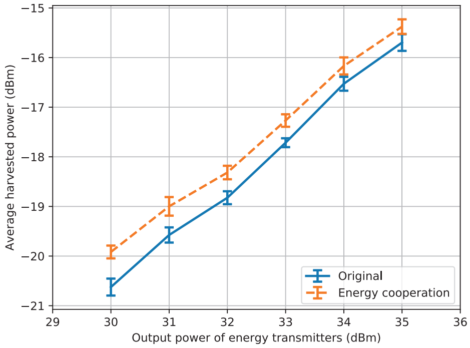


Fig. 6. Average harvested power with different output power of energy transmitters

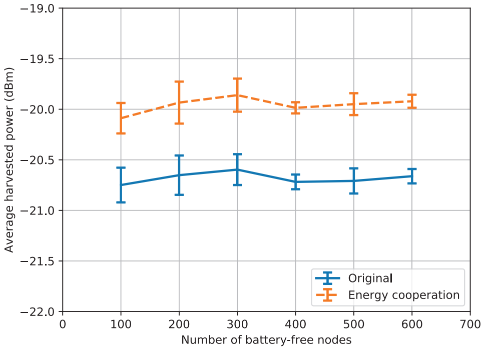


Fig. 7. Average harvested power with different number of nodes

Then, we study the harvested energy of nodes with original mode and energy cooperation protocols. We test the harvested power of every node in the default settings and the cumulative distribution function (CDF) results are shown in Fig. 5. Compared to the original protocol, the harvested energy of each node is increased by the energy cooperation protocol. From the result, we find that the harvested power of node which harvests lower energy is increased more significantly than the one which harvests higher energy in the original mode. The harvested power of nodes which harvests -23dBm to -21dBm are increased most obviously by the energy cooperation solution.

We also test the average harvested power in the simulations. As shown in Fig. 6, we first test average harvested power with different output power settings of energy transmitters. We adjust the output power of energy transmitters from 30dBm to 35dBm. From the result, we find the energy cooperation increases the average harvested power of battery-free nodes. With a lower output power of energy transmitters, the average harvested power of battery-free nodes is increased more obvious. As a result, the energy cooperation protocol performs better with lower power from the energy transmitters.

Then, we test the average harvested power with different numbers of battery-free nodes. We maintain the output power of energy transmitters as 30dBm and change the number

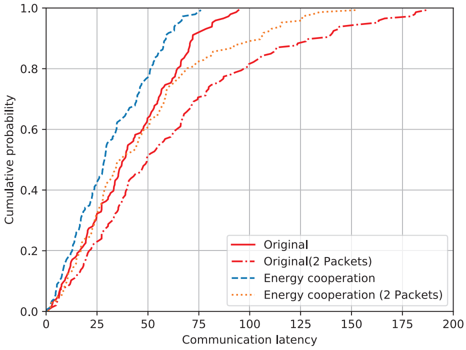


Fig. 8. Cumulative probability of communication latency

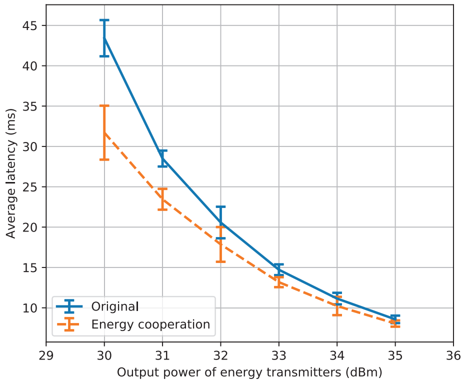


Fig. 9. Average latency with different output power of energy transmitters

of battery-free nodes from 100 to 600 and increase 100 nodes in each step. As shown in Fig. 7, the average harvested power is slightly increased by energy cooperation protocol. With different numbers of nodes, the increased harvested power stays similar and average is about 0.5dBm or 1.12 times than the original mode.

As this paper focus on the latency in data communications, we test the communication latency in the simulations. As shown in Fig. 8, we first study the cumulative probability of communication latency. From the result, the network latency is significantly decreased by the energy cooperation protocol. The network performance of nodes with higher latency is improved more obviously than nodes with lower latency. Thus, the energy cooperation protocol is a potential solution to improve the quality-of-service (QoS) of the battery-free wireless networks. Moreover, we also study network latency when two packets are being transmitted in the network. The network latency increases with transmitting more packets. With more packets transmitted in the network, energy cooperation still performs better than original model with lower network latency.

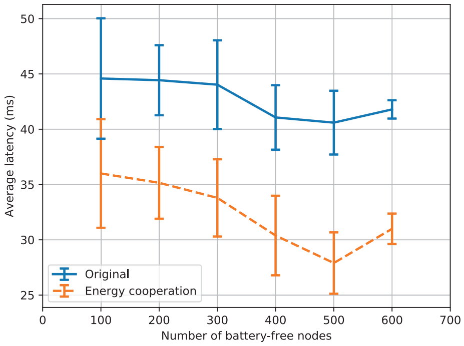


Fig. 10. Average latency with different number of nodes

As shown in Fig. 9, we test the average communication latency with different output powers. We maintain the number of nodes is 200 and adjust the output energy of energy transmitters from 30dBm to 35dBm and add 1dBm in each step. The average latency is also significantly decreased by the energy cooperation protocol with different output powers of energy transmitters. The decreased average latency is about 4 ms with the output power of 30dBm. When the output power increased, as the overall network performance becomes better, the decreased average latency is not so obvious than the result of lower output energy.

We then adjust the number of nodes in the network and maintain the output power of energy transmitters stays 30dBm. We set the number of nodes from 100 to 600 and increase 100 in each step. As shown in Fig. 10, the average latency is significantly decreased by the energy cooperation protocol. When the number of nodes is less than 600, the decreased latency is increased with the increasing number of nodes. When the number of nodes is 600, the latency with both original and energy cooperation protocols slightly increases. We consider its reason is because the average number of forwarding hops is increased by the increasing number of nodes. As a result, the energy cooperation protocol can decrease the 5ms or about 15% of the average network latency.

7 CONCLUSION AND FUTURE WORK

In this paper, we propose an energy cooperation scheme in battery-free wireless networks with RF energy harvesting to improve the network performance by decreasing the communication latency. We first introduce the scenario of the battery-free wireless network and RF energy harvesting and discuss the problem of the energy cooperation in this scenario. We state a problem to decrease the network latency by energy cooperation then design an energy cooperation protocol to solve the problem. We also theoretically analyze proposed protocol and evaluate its performance through extensive simulations. Both theoretical and numerical results show that our energy cooperation protocols perform better than the original network with shorter network latency.

In the future, we plan to implement a complete RF energy harvesting solution for battery-free networks to support energy cooperation. Meanwhile, it is signification to find appropriate routing protocol to combine the energy cooperation and packet forwarding. A deeper experiment with the real word testbed is also needed to evaluate the efficiency of the new energy cooperation protocol.

ACKNOWLEDGMENTS

This work is supported by JSPS KAKENHI Grant Number JP16K00117, JP15K15976, JP17K12669, KDDI Foundation, and Research Fund for Postdoctoral Program of Muroran Institute of Technology. Mianxiong Dong is the corresponding author.

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