Using Range Extension Cooperative Transmission in Energy Harvesting Wireless Sensor Networks

Jin Woo Jung and Mary Ann Ingram

Abstract: **In this paper, we study the advantages of using range extension cooperative transmission (CT) in multi-hop energy harvesting wireless sensor networks (EH-WSNs) from the network layer perspective. EH-WSNs rely on harvested energy, and therefore, if a required service is energy-intensive, the network may not be able to support the service successfully. We show that CT networks that utilize both range extension CT and non-CT routing can successfully support services that cannot be supported by non-CT networks. For a two-hop toy network, we show that range extension CT can provide better services than non-CT. Then, we provide a method of determining the supportable services that can be achieved by using optimal non-CT and CT routing protocols for EH-WSNs. Using our method and network simulations, we justify our claim that CT networks can provide better services than non-CT networks in EH-WSNs.**

Index Terms: **Cooperative transmission (CT), energy harvesting, wireless sensor networks.**

I. INTRODUCTION

In energy harvesting wireless sensor networks (EH-WSNs), a network can successfully serve its purpose as long as nodes can sufficiently replenish their energies so that all required data can be collected by the gateway nodes (sink nodes). Unless hardware fails, EH-WSNs can last forever, and therefore, in EH-WSNs, the important question is, can the network successfully serve its purpose? The energy consumption of each node, which strongly affects the network's ability to complete its tasks, depends on not only the hardware but also the applications, network topology, and communication protocols. In event-detection applications [1], the energy consumption of a node depends on how frequently the event occurs, and, if the application includes periodic reporting [2], such as in the building energy management application [3], a node is required to send its sensed data to sink nodes during each reporting period. Since it is possible that the event in an event-detection application may never occur, we consider the periodic reporting applications where every node has its mandatory tasks, i.e., sensing and transmitting data to sink nodes, in this paper. The network topology, which can be either single-hop or multi-hop, also impacts the energy consumption of nodes because, in the case of multi-hop networks, some nodes have to use their energies to relay other nodes' data, which has a nontrivial impact on the energy consumption of the relaying nodes and which is unnecessary for single-hop networks. Since the communication range of a sensor node is limited, e.g., the popular MicaZ [4] has an indoor range of 20-30 m and an outdoor range of 75-100 m, if sensors are deployed in a large area with only one or a few sink nodes, the network has to be multi-hop, and therefore, in this paper, we consider multi-hop networks where the energy requirement is more demanding than that of the single-hop networks. Moreover, we mainly focus on the network having one sink node, which is the worst case scenario from the energy consumption point of view because, if there are multiple sink nodes, the traffic can be distributed to one of the destinations to better balance the energy consumption. Communication protocols can also lead to different energy consumptions of nodes, and many researchers have proposed methods of saving and using the available energy wisely through communication protocols. In the medium access control (MAC) layer, duty-cycled MAC schemes [5]–[9] have been developed to reduce the power consumption of the nodes by putting nodes into sleep as long as possible. In the network layer, energy-aware routing schemes [10]–[13] have been proposed to extend the network lifetime by using the nodes with high residual energies while minimizing the total energy consumption.

In this paper, we study the advantages of using cooperative transmission (CT) [14] for multi-hop EH-WSNs from the network layer perspective. CT is a mixture of a communication protocol and a physical layer combining scheme that can create a virtual multiple-input-single-output (VMISO) system by utilizing multiple single-antenna communication devices. Through the communicating protocol of CT, the data of one transmitting node is shared with selected neighbors, and the shared data is transmitted by these neighbors and the transmitting node. The receiving node, by combining the multiple transmitted data, gets diversity and array gains, which lead to a signal-to-noise ratio (SNR) advantage over the traditional single-input-single-output (SISO) case [14]. CT's SNR advantage can be used to reduce the transmit powers of transmitting nodes [15]–[18]. However, for widely used sensor radios such as CC2420 [19], the radiated energy is just a small portion of total energy consumption, and, in this case, reducing power through CT cannot be an energy-efficient strategy because, unlike non-CT, CT has to pay the extra cost of the circuit energy consumptions of the cooperating nodes. CT's SNR advantage can also be used to extend the SISO communication range (which we refer to as "range extension CT") [20], [21], [22], and, in [23], we have designed a cooperative routing protocol, REACT, that uses CT's extended range to relieve the relay burden of bottleneck nodes and extend the network lifetime. In [24], considering energy harvesting networks, we have shown the possibility of providing better services, i.e., supporting larger networks and reporting data more frequently,

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when REACT is used compared to a non-CT energy-aware routing scheme. In [24], we derived the required duty cycle for every node to ensure support of service, and, through network simulation, we showed whether or not a service can be successfully provided by checking if every node in the network can meet a duty cycle threshold that is consistent with the amount of energy that can be harvested.

This paper, unlike [24], adopts a more systematic approach to show the benefits of using range extension CT for energy harvesting networks. For a simple two-hop network, we show through analysis and simulation that the range extension CT can provide better services compared to non-CT. Then, we introduce a method of determining the service levels that can be achieved by using an optimal routing protocol when energy harvesting is possible for both CT and non-CT networks. Note that the method provided in this paper overcomes several shortcomings of the approach that we have used in [24], which are i) the approach in [24] obtains the duty cycle upper bound, which may not be obtained easily especially when the harvesting rate is time-varying and ii) the approach in [24] relies on the network simulation results of selected routing protocols, however, there is no guarantee that selected routing schemes are optimal under the given circumstances. The method presented in this paper, which is simple and does not rely on network simulations, can determine an upper bound on the supportable service when a network can have an optimal routing protocol for energy harvesting networks. Finally, we provide the results of the decision method and network simulations that clearly justify our claim that range extension CT can provide better services than non-CT.

This paper is organized as follows. Section II defines conditions and terms that are used in this paper. In Section III, we discuss the possibility of using range extension CT to provide better services compared to non-CT for a simple two-hop EH-WSNs. A method of determining the supportable services that can be achieved by using an optimal routing protocol for energy harvesting CT and non-CT networks is developed in Section IV. We evaluate our method and provide network simulation results in Section V, and concluding remarks are in Section VI.

II. ASSUMPTIONS AND DEFINITIONS

We consider single commodity multi-hop EH-WSNs that run periodic reporting applications. Sensed data is gathered at sink nodes which have no energy constraints, and a node except for sink nodes is energy-constrained, has energy harvesting capability, and has to report sensed data periodically, with period T_{RP}. In EH-WSNs, the network operator wishes to run the network for several years or decades, and the amount of the desirable network lifetime will be referred to as the required service period, and we denote the required service period as T_{serv}. $E_{\text{Data}}^{\text{TX}}$, $E_{\text{Data}}^{\text{RX}}$, $E_{\text{Ack}}^{\text{TX}}$, $E_{\text{Ack}}^{\text{RX}}$, and E_{Sen} are the energy consumptions for data transmission, data reception, acknowledgment transmission, acknowledgment reception, and sensing, respectively. We use P and T for the power and time values respectively that correspond to the energy value E. For example, the power and time values for $E_{\text{Data}}^{\text{TX}}$ are denoted as $P_{\text{Data}}^{\text{TX}}$ and $T_{\text{Data}}^{\text{TX}}$, respectively.

We look at the problem from the network layer perspective, and we consider i) the network that does not use CT (the "non-CT network") and ii) the network where both CT and non-CT are supported by the protocols (the "CT network"). Using the techniques of other layers such as data aggregation and compression are not considered for both non-CT and CT networks in this paper. For the CT network, we consider the case where CT is used to extend the communication range, and we use the following conditions and definitions. A node, when it has a data to be transmitted, can either do CT by cooperating with its selected neighbors or do non-CT by sending its data to one of its neighbors. Neighbors of a node are the ones that are within SISO (non-CT) communication range of the node, and cooperators of a node are the neighbors of the node that are selected by the node to do CT. If a node decides to do CT, it becomes a CT initiator (or just "initiator"), and it first sends its data to selected cooperators, and then it performs CT with the selected cooperators to send the data to the destination. The link established using CT will be referred to as the VMISO link. The initiator and its cooperators transmit data to the VMISO destination using orthogonal channels [14]. A VMISO link can be formed between the 'cooperating nodes' (this term is different from the word cooperators because it includes cooperators and the initiator) and one of the sink nodes, which is the method that we have used in [23]. Also, following [23] and [25], we assume that a sink node can reach any node using SISO (non-CT) communication. The maximum number of cooperating nodes, denoted as $N_c^{\max}$, cannot exceed the maximum number of orthogonal diversity channels, and therefore, an initiator can select up to $N_c^{\max} - 1$ cooperators.

To calculate the amount of range extension that can be obtained from CT, we take the following physical-layer approach that is similar to that of [21]. We assume a set of channel propagation parameters based on measurements in [20], which are representative of indoor scenarios [26]. Specifically, we assume a path loss exponent of 2.9, Rayleigh fading, log-normal shadowing with a standard deviation of 5 dB, and BPSK modulation. For these parameters, we calculate via simulation the required SNR to achieve an average bit error rate (ABER) of 10^{-3}, for each of the VMISO link and the SISO link, assuming coherent combining in the receiver of the VMISO link. Because of diversity and array gains, the required SNR for VMISO is significantly less than that of SISO; the difference is the SNR advantage of CT. Using the path loss model, we calculate the increase in distance that would cause the SNR to decrease by the same amount; this is the amount of range extension we assume.

The "service requirement" or "required service" indicates that all data generated by source nodes should be delivered to sink nodes during T_{serv}. If the network can meet the service requirement for given network topology and T_{RP}, the service is *supportable*. The supportable service depends mainly on the network topology and T_{RP}, and the "upper bound" of the supportable service of a network is either the maximum size of the network for a given T_{RP} or the lowest value of T_{RP} for a given network topology that the network can support. A network is considered to provide a *better* service than the other if, given a fixed number of sink nodes, it can support either a larger network (provide better sensing coverage) or smaller T_{RP} (more frequent data gathering).

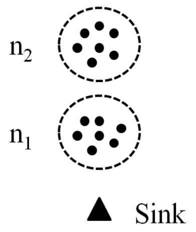


Fig. 1. A simple two-hop network. There are n_1 nodes in Level 1 and n_2 nodes in Level 2. Any nodes in Level 1 and Level 2 can talk to each other.

III. ANALYSIS OF A SIMPLE TWO-HOP NETWORK

In this section, we discuss the possibility of using range extension CT to provide better services than non-CT through a brief analysis. Let us denote the harvested energy during T_{RP} as E_{EH}. In this section, we assume that E_{EH} is constant for all nodes. During T_{RP}, a node must consume energy for sensing and transmitting (its own sensed data), denoted as E_{ST}, and E_{ST} = $E^{\text{TX}}_{\text{Data}} + E^{\text{RX}}_{\text{Ack}} + E_{\text{Sen}}$. Let E_A=$E_{\text{EH}} - E_{\text{ST}}$ be the available energy that each node can use during T_{RP} (because E_{ST} must be used during T_{RP}). We assume that nodes do not have any energy at the beginning, and they have to rely on the harvested energy to operate. When a node is i hops away from the sink node, we say that the node is in "Level i." Here, the hop count is determined based on the SISO communication range.

Let us consider a simple two-hop network in Fig. 1, where there are n_1 nodes in Level 1 and n_2 nodes in Level 2. In Fig. 1, we assume that each node in Level 2 can communicate with any node in Level 1 and Level 2. We also assume that the incoming traffic (relay traffic) of nodes in Level 1 is distributed as equally as possible. In this case, some nodes in Level 1 must relay $\lceil \frac{n_2}{n_1} \rceil$ messages, whereas the rest can relay only $\lfloor \frac{n_2}{n_1} \rfloor$ messages. Therefore, in the worst case, a node in Level 1 must relay $\lceil \frac{n_2}{n_1} \rceil$ messages.

Now, let us consider the number of relay messages that a node in Level 1 can handle during the time interval [0, T_{RP}]. We note that relaying is a distinct operation from "sensing and transmitting." When a node relays, it consumes $E_{\text{Relay}} = P^{\text{TX}}_{\text{Data}} T^{\text{TX}}_{\text{Data}} + P^{\text{RX}}_{\text{Data}} T^{\text{RX}}_{\text{Data}} + P^{\text{TX}}_{\text{Ack}} T^{\text{TX}}_{\text{Ack}} + P^{\text{RX}}_{\text{Ack}} T^{\text{RX}}_{\text{Ack}}$. Therefore, a node can relay $\lfloor E_A/E_{\text{Relay}} \rfloor$ messages, and this number should be larger than $\lceil \frac{n_2}{n_1} \rceil$ (the worst case), which leads to the following condition.

$$\left\lceil \frac{n_2}{n_1} \right\rceil \le \left\lfloor \frac{E_{\text{A}}}{E_{\text{Relay}}} \right\rfloor \triangleq K. \tag{1}$$

Now, let us consider the case where the nodes in Level 2 form a VMISO link directly to the sink node by using range extension CT so that the relay burden of the nodes in Level 1 can be reduced. We assume that two cooperating nodes are enough to form a VMISO link to the sink node. If we assume that n_x nodes ($n_x \le n_2$) in Level 2 initiate CT for their sensed data so that n_x packets do not have to be relayed by the nodes in Level 1, then the nodes in Level 1 have to take care of only $\lceil \frac{n_2 - n_x}{n_1} \rceil$ relay messages during T_{RP} in the worst case, which leads to the following condition:

$$\left\lceil \frac{n_2 - n_x}{n_1} \right\rceil \le K. \tag{2}$$

Let us assume that $n_x \le \frac{1}{2} n_2$ so that the sets of initiators and cooperators can be two mutually exclusive sets. In other words, there will be n_x initiators and n_x cooperators among n_2 nodes in Level 2, and none of them are the same node. An initiator that decides to do CT for transmitting its own sensed data, has to consume its energy for i) data sharing, denoted as $E^{\text{TX}}_{\text{SH}}$, which is $P^{\text{TX}}_{\text{Data}} T^{\text{TX}}_{\text{Data}} + P^{\text{RX}}_{\text{Ack}} T^{\text{RX}}_{\text{Ack}}$, and ii) doing CT with its cooperator, denoted as $E^{\text{TX}}_{\text{CT}}$, which is $P^{\text{TX}}_{\text{Data}} T^{\text{TX}}_{\text{Data}} + P^{\text{RX}}_{\text{Ack}} T^{\text{RX}}_{\text{Ack}}$. Note that, since the initiator sends its sensed data through CT, $E^{\text{TX}}_{\text{CT}}$ should be considered as already included in E_{ST} of E_{A}, and therefore, an initiator has to use an $E^{\text{TX}}_{\text{SH}}$ out of its available energy. The cooperator that sends its sensed data using non-CT and has to do CT for the initiator's sensed data additionally must consume its energy for receiving CT sharing message, denoted as $E^{\text{RX}}_{\text{SH}}$, which requires $P^{\text{RX}}_{\text{Data}} T^{\text{RX}}_{\text{Data}} + P^{\text{TX}}_{\text{Ack}} T^{\text{TX}}_{\text{Ack}}$ and ii) doing CT with the initiator, which requires $E^{\text{TX}}_{\text{CT}}$. Therefore, a cooperator has to use $E^{\text{RX}}_{\text{SH}}$+$E^{\text{TX}}_{\text{CT}}$ out of its available energy, and this is the worst case energy consumption for the nodes in Level 2. Note that each cooperator handles exactly one CT (n_x CT instances are distributed to n_x cooperators), so $E^{\text{RX}}_{\text{SH}} + E^{\text{TX}}_{\text{CT}} \le E_A$ should hold, which can be rewritten as

$$1 \le \frac{E_{\text{A}}}{E^{\text{RX}}_{\text{SH}} + E^{\text{TX}}_{\text{CT}}} = \frac{E_{\text{A}}}{E_{\text{Relay}}}. \tag{3}$$

As long as (2) and (3) hold, the nodes in Level 2 can successfully perform n_x CT instances where $n_x \le \frac{1}{2} n_2$. Note that $\lceil \frac{n_2}{n_1} \rceil \ge 1$, which means that the condition for non-CT in (1) already implies (3). It is also obvious that if (1) holds, so does (2). Therefore, if (1) holds, which means that non-CT can support the required service, doing CT for n_x times in Level 2 is also possible.

Now, let us consider the number of nodes in Level 2 that the network can support for CT and non-CT. From (1), we can get $n_2 \le K n_1$ for non-CT, and, from (2), we get $n_2 \le K n_1 + n_x$ for CT. This means that, for given K and n_1, CT can support n_x more nodes compared to non-CT where $n_x \le \frac{1}{2} n_2$. In other words, in CT networks, $100 \times n_2 / \{2(n_1 + n_2)\}$ percent more nodes can be supported compared to non-CT networks for the network in Fig. 1.

Let us consider the reporting period T_{RP}. Low T_{RP} means that the sensed data can be gathered more frequently, which lets us have more up-to-date status. We plot K's for different T_{RP}'s (in seconds) in Fig. 2 using the values in Table 1, which are measured values of real energy harvesters and sensor devices [27], [28]. More specifically, the measurements are obtained by using Tyndall motes with temperature/humidity sensors, Sensirion SHT71, and dual-axis accelerometers, Analog Devices ADXL250 [27]. Also, $P_{\text{EH}} = (P_{\text{PV}} \times \eta_{\text{MPPT}} - P_{\text{Leak}}) \times \eta_{\text{SR}}$, where $P_{\text{PV}} = 382\ \mu W$ is the maximum output of a Sanyo AM1815 solar panel under 500 Lux fluorescent light, $\eta_{\text{MPPT}} = 90.5\%$ is the maximum power point tracker efficiency, $P_{\text{Leak}} = 35 \mu W$ is the average leakage power of Maxwell BCAP0005 supercapacitor, and $\eta_{\text{SR}} = 51\%$ is the average conversion efficiency of TI TPS61220 switching regulator [28].

As can be seen from the figure, K is a monotonically increasing function of T_{RP}, and, in order to support low T_{RP}, K should be low. For, K=0, (1) and (3) are violated, and therefore, both CT and non-CT networks cannot support $T_{\text{RP}} \le 100$. For K=1 ($110 \le T_{\text{RP}} \le 160$), non-CT should satisfy $\lceil \frac{n_2}{n_1} \rceil \le 1$

Table 1. Power and time values.

Power (mWatt)		Time (msec)	
$P_{\text{Data}}^{\text{TX}}$ = 131.4	$P_{\text{Ack}}^{\text{TX}}$ = 111.1	$T_{\text{Data}}^{\text{TX}}$ = 35	$T_{\text{Ack}}^{\text{TX}}$ = 0.45
$P_{\text{Data}}^{\text{RX}}$ = 174.3	$P_{\text{Ack}}^{\text{RX}}$ = 133.3	$T_{\text{Data}}^{\text{RX}}$ = 35	$T_{\text{Ack}}^{\text{TX}}$ = 0.45
P_{Sen} = 53.3	P_{EH} = 0.1585	T_{Sen} = 7.5	

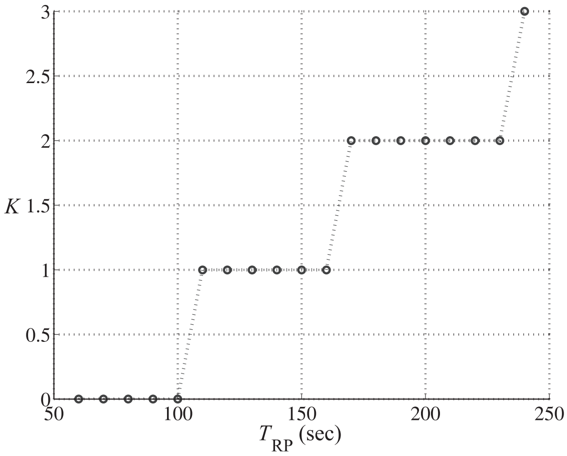


Fig. 2. The values of K for different reporting periods.

and CT should satisfy $\lceil \frac{n_2 - n_x}{n_1} \rceil \leq 1$ (when K=1, (3) readily holds). Therefore, when $n_2 \leq n_1$, or equivalently, $\lceil \frac{n_2}{n_1} \rceil = 1$, both CT and non-CT networks can support T_{RP}=110 secs. When $\frac{1}{2}n_2 \leq n_1 < n_2$, or equivalently, $\lceil \frac{n_2}{n_1} \rceil = 2$, (1) forces K to be 2 and non-CT network can only support as low as T_{RP}=170 secs, whereas, since $\lceil \frac{n_2 - n_x}{n_1} \rceil$ is still less than or equal to one because $n_x \leq \frac{1}{2}n_2$, CT can still have K=1 meaning CT network can still support T_{RP}=110 secs, which is shorter than 170 secs of non-CT networks. Therefore, in the case of CT networks, it is possible that data can be reported more frequently than non-CT networks.

Using the simple two-hop network in Fig. 1, we have seen that the range extension CT can support more nodes and more frequent data gathering than non-CT for periodic reporting applications. Note that the analysis made in this section is considering a simple network, which cannot be considered as a general network topology. Therefore, what we have shown in this section is the *possibility* of providing better services using range extension CT compared to non-CT. In the following section, we introduce a method of determining the supportable services that can be achieved by using an optimal routing protocol when energy harvesting is possible for both CT and non-CT networks.

IV. DETERMINING SUPPORTABLE SERVICES FOR ENERGY HARVESTING NETWORKS

In this section, we first review the lifetime optimization problem of non-CT routing for *non-energy harvesting* networks developed in [29]. Then, by using the fact that an optimal routing for EH-WSNs should be able to deliver all the required data to the sink nodes, we modify the conditions of [29] and develop a method of determining supportable services for EH-WSNs networks.

We use the following variables throughout this section. Let A be the set of all nodes in the network, S_i be the set of neighbors of node i, D be the set of destination nodes, and E be the set of nodes that are not energy-constrained. In WSNs, D is the set of sink nodes. The total number of source nodes in the network will be denoted as N_s $(= |A| - |D|)$. We define n_{ij} as the total number of data packets transmitted from Node i to node j until the lifetime T of the network (the lifetime of the network is the time that the first node dies [29]). Also we define e_{ij}^{TX} as the required energy for node i to transmit a data packet from node i to node j, e_{ji}^{RX} as the required energy for node i to receive a data packet coming from node j, e_i^{gen} as the energy consumption for generating a data packet denoted, Q_i as the information generation rate of node i, and E_i as the initial energy of node i.

A. Review of non-CT lifetime optimization for non-energy harvesting networks

The energy constraint condition in [29] states that the total energy consumption during the network lifetime T for node i cannot exceed E_i, which leads to the following condition[1]:

$$(TQ_i)e_i^{\text{gen}} + \sum_{j \in S_i} e_{ij}^{\text{TX}} n_{ij} + \sum_{j: i \in S_j} e_{ji}^{\text{RX}} n_{ji} \leq E_i. \quad (4)$$

Then, the lifetime optimization problem of non-CT routing for energy-constrained networks can be formulated using linear programming (LP) as follows [29]:

$$\begin{aligned}
&\text{Maximize } T \\
&\quad \text{s.t. } n_{ij} \geq 0, \ \forall i \in A, \forall j \in S_i, && (5)\\
&\qquad (TQ_i)e_i^{\text{gen}} + \sum_{j \in S_i} e_{ij}^{\text{TX}} n_{ij} + \sum_{j: i \in S_j} e_{ji}^{\text{RX}} n_{ji} \leq E_i, \\
&\qquad \forall i \in A - E, && (6)\\
&\qquad \sum_{j: i \in S_j} n_{ji} + TQ_i = \sum_{j \in S_i} n_{ij}, \forall i \in A - D && (7)
\end{aligned}$$

where the LP variables are expressed in terms of number of data packets n_{ij} as in [30], and (7) is the data conservation (flow conservation) condition of node i (we are directly looking at the amount of data instead of flows). Note that TQ_i is the number of data packets generated by node i during the lifetime of the network.

B. Determining Supportable Services for Energy Harvesting Networks

In the case of energy harvesting networks, we are no longer looking at the lifetime maximization, and whether one can get the required services in the service period (T_{serv}) is important. Here, we wish to develop a method that determines whether optimal non-CT and CT routing protocols can support required services in energy harvesting networks, and we achieve this goal by considering and modifying the conditions discussed in the previous section.

[1] e_i^{gen} is not included in [29]. We include e_i^{gen} in (4) for the better modeling of Node i's energy consumption.

Let us first consider the case of non-CT networks. In any sensor application, it is important that all required data reaches the sink nodes successfully during T_{serv}. The total number of received data during T_{serv} for non-CT networks can be expressed as

$$\sum_{k:k\in D}\sum_{j:k\in S_j} n_{jk} \tag{8}$$

where, n_{ij} is redefined as the total number of data packets transmitted from Node i to Node j until T_{serv} instead of T ($T = T_{\text{serv}}$). For periodic reporting applications, we want the sink nodes to receive a total of $N_s\lfloor T_{\text{serv}}/T_{\text{RP}}\rfloor$ packets at least[2]. In order to eliminate the ambiguity of the required number of packets to be received, we assume that T_{serv} is a multiple of T_{RP} from now on, and, for the service time of T_{serv}, a total of $N_s \cdot T_{\text{serv}}/T_{\text{RP}}$ packets should be delivered to the sink nodes.

The energy constraint condition of Node i when energy harvesting is possible is as follows:

$$\begin{aligned}&(T_{\text{serv}}Q_i)e_i^{\text{gen}} + \sum_{j\in S_i} e_{ij}^{\text{TX}} n_{ij} + \sum_{j:i\in S_j} e_{ji}^{\text{RX}} n_{ji}\\ &-(T_{\text{serv}}H_i) \le E_i, \quad \forall i \in A - E\end{aligned} \tag{9}$$

where H_i is the time-averaged harvesting rate of Node i in Joules/sec, so that $T_{\text{serv}}H_i$ is the overall harvested energy during T_{serv}. Note that maximizing (8), when combined with the energy constraint condition and the data conservation condition, captures the optimized routing behavior for energy harvesting networks.

From the above discussions, we formulate the following LP for non-CT energy harvesting networks as

$$\begin{aligned}&\text{Maximize } (8)\\ &\text{s.t. } (5), (9),\\ &\sum_{j:i\in S_j} n_{ji} + T_{\text{serv}}Q_i = \sum_{j\in S_i} n_{ij}, \ \ \forall i \in A - D,\end{aligned} \tag{10}$$

and if (8) = $N_s T_{\text{serv}}/T_{\text{RP}}$, the optimal non-CT routing scheme can support the required service during T_{serv}. Note that (9) does not consider the capacity limit of the energy storage device, and we argue that not considering the capacity limit does not critically harm the objective of the above method because of the following reason. Whether (8) can meet $N_s T_{\text{serv}}/T_{\text{RP}}$ or not is dependent on the nodes that get relatively low energy reserves (compared to other nodes) as time goes by. In other words, (8) cannot have $N_s \cdot T_{\text{serv}}/T_{\text{RP}}$ when the nodes with relatively low energy reserves do not have energy to complete all their packet sending tasks. Those nodes usually cannot reach their capacity limits, and therefore, they should not be affected by having storage capacity limit or not. Also, even if there are situations that those nodes reach their capacity limits, the above method can still give upper bound on the supportable services because it assumes the case of an ideal storage device. Note that, unlike T, T_{serv} is not an LP variable. Also, for periodic reporting applications, $Q_i = 1/T_{\text{RP}}$ for all $i \in A - D$. This means that the above LP formulation already implies that each node is able to generate $T_{\text{serv}}/T_{\text{RP}}$ (= $T_{\text{serv}}Q_i$) packets and transmit them to sink nodes during T_{serv}, and, when the LP solution exists, (8) = $N_s T_{\text{serv}}/T_{\text{RP}}$. Therefore, when the solution of the above LP exists, there exists an optimal non-CT routing scheme that enables the non-CT network to support the required service, and when the solution does not exist, non-CT networks cannot support the required service. Note that this also suggests that one can determine whether non-CT can support the required service or not by checking whether a feasible solution exists for the linear equalities and inequalities of (5), (9), and (10), which does not necessarily require LP formulation and solution.

Now, let us move on to the case of CT networks. In this case, packets can also be transmitted via VMISO links where the VMISO destination is a sink node. For a node to form VMISO link, it requires at least N cooperators where $1 \le N \le N_c^{\max} - 1$. We denote $R_{i,d}^N$ as the set of N-tuples, $(r_1, r_2, \cdots, r_N)$, where $r_m \in S_i$ ($1 \le m \le N$) and each tuple indicates the combination of cooperators that can reach node d ($d \in D$) directly by cooperating with the initiator, node i. We denote the k-th tuple in $R_{i,d}^N$ as $R_{i,d}^{N,k}$, and we define the total number of data packets that Node i transmits to the VMISO destination d during T_{serv} by cooperating with the nodes in $R_{i,d}^{N,k}$ as $n_{i,d}^{N,k}$. When Node i is an initiator, the related total energy consumption during T_{serv} is

$$\sum_{d:d\in D}\sum_{N=1}^{N_c^{\max}-1}\sum_{k=1}^{|R_{i,d}^{N,k}|} n_{i,d}^{N,k}(E_{\text{CT}}^{\text{TX}} + E_{\text{SH}}^{\text{TX}}), \tag{11}$$

and, when Node i is a cooperator of an initiator, the related total energy consumption during T_{serv} is

$$\sum_{d:d\in D}\sum_{N=1}^{N_c^{\max}-1}\sum_{k:i\in R_{j,d}^{N,k}} n_{j,d}^{N,k}(E_{\text{SH}}^{\text{RX}} + E_{\text{CT}}^{\text{TX}}). \tag{12}$$

Therefore, the energy constraint condition of Node i when energy harvesting and range extension CT are possible is as follows:

$$\begin{aligned}&(T_{\text{serv}}Q_i)e_i^{\text{gen}} + \sum_{j\in S_i} e_{ij}^{\text{TX}} n_{ij} + \sum_{j:i\in S_j} e_{ji}^{\text{RX}} n_{ji}\\ &-(T_{\text{serv}}H_i) + (11) + (12) \le E_i, \qquad \forall i \in A - E.\end{aligned} \tag{13}$$

The total number of incoming data packets of Node i when CT is used has the same formulation as non-CT (the VMISO reception is done only by the sink nodes), however, outgoing packets of Node i can be transmitted either directly to the destination using CT or to a neighbor using non-CT, which leads to the following data conservation condition for Node i:

$$\begin{aligned}&\sum_{j:i\in S_j} n_{ji} + T_{\text{serv}}Q_i = \sum_{j\in S_i} n_{ij}\\ &+\sum_{d:d\in D}\sum_{N=1}^{N_c^{\max}-1}\sum_{k=1}^{|R_{i,d}^{N,k}|} n_{i,d}^{N,k}, \qquad \forall i \in A - D.\end{aligned} \tag{14}$$

Therefore, the required conditions for range extension CT are (5), (13), (14), and

[2]The total number of received packets should be between $N_s \cdot \lfloor T_{\text{serv}}/T_{\text{RP}}\rfloor$ and $N_s\lceil T_{\text{serv}}/T_{\text{RP}}\rceil$ depending on T_{serv} and the time each node reports its data.

$$n_{i,d}^{N,k} \geq 0, \qquad \forall i \in A - D, d \in D, R_{i,d}^{N} \neq \{\}, \tag{15}$$

and if the feasible solution exists for the above conditions, CT networks can support the required service. Note that the above required conditions for CT are same as those of non-CT when $n_{i,d}^{N,k}$'s are not considered, and therefore, the above conditions can be used for checking whether a service requirement can be met or not for both non-CT (by ignoring $n_{i,d}^{N,k}$) and CT networks. Again, one of the ways to check the feasibility of the conditions is to formulate and solve LP that maximizes the total number of packets received by sink nodes. Note that, in the case of the range extension CT, the total number of packets received by sink nodes should include $n_{i,d}^{N,k}$'s along with (8). We will refer to the method that can determine the supportable service for CT and non-CT networks using the above conditions as the "condition-based decision (CBD)" from now on. Also, the conclusion drawn from CBD will be referred to as the "CBD result".

Note that the LP formulation in [29] that we have introduced in Section IV-A can also provide the optimal lifetime for time-varying data generation rate because it considers total number of generated data during network lifetime (TQ_i) in its problem formulation (in (7)), and the formulation is not restricted to periodic reporting applications. Likewise, our CBD introduced in this section can be used for any applications including periodic reporting applications.

V. EVALUATION

In this section, we verify our claim that range extension CT can provide better services than non-CT in EH-WSNs by using CBD and performing network simulations. By comparing the results of network simulations with those of CBD, we show that CBD successfully provides the upper bounds of the supportable services for CT and non-CT networks. For the network simulations, we use the online non-CT routing protocol, E-WME[3], in [13] and the online CT routing protocol, REACT[4], in [23], and we observe the throughput and energy behaviors of these two protocols. For the non-CT primary routing scheme for REACT, we use E-WME.

We use the following conditions and assumptions throughout the entire section. As mentioned earlier, we use multi-hop networks having a single sink node to consider the worst-case energy consumption scenario. Note that neither CBD in Section IV, nor REACT, nor E-WME requires to have a single sink in the network. We use the values in Table 1 for our network simulations assuming a fixed transmit power. Neither the CBD, nor REACT nor E-WME is restricted to the fixed transmit power case, however, we use a fixed transmit power because, as we have mentioned earlier, the radiated energy for existing sensor radios usually has a minor contribution to the total energy consumption. Since we are particularly interested in comparing the network protocols and there are many different ways to implement MAC layer, we do not consider any energy consumption regarding MAC except for the ACK packet communication for both non-CT and CT. For CBD, e_i^{gen}=E_{Sen}, e_{ij}^{TX}=$E_{\text{Data}}^{\text{TX}} + E_{\text{Ack}}^{\text{RX}}$, e_{ji}^{RX}=$E_{\text{Data}}^{\text{RX}} + E_{\text{Ack}}^{\text{TX}}$, $E_{\text{SH}}^{\text{TX}}$=$E_{\text{Data}}^{\text{TX}} + E_{\text{Ack}}^{\text{RX}}$, and $E_{\text{SH}}^{\text{RX}}$=$E_{\text{Data}}^{\text{RX}} + E_{\text{Ack}}^{\text{TX}}$ are used. For diversity order larger than 2, full rate STBC does not exist, and the best achievable rate for the diversity order of 3 and 4 is 3/4. Therefore, when cooperating nodes are 3 or 4, (N=2 or 3), we use $T_{\text{Data}}^{\text{TX}}4/3$ (and corresponding $E_{\text{Data}}^{\text{TX}}$) for CBD and network simulations, and $E_{\text{CT}}^{\text{TX}}$=$E_{\text{Data}}^{\text{TX}} + E_{\text{Ack}}^{\text{RX}}$.

All nodes have the same SISO maximum transmission range of $d_{\text{tx}}^{\max}$=25m, and a SISO link exists from Node i to Node j if Node j is within $d_{\text{tx}}^{\max}$ from Node i. This makes links deterministic. In [23], we derived d_{req}, which can be used to determine whether a VMISO link can be formed between cooperating nodes and a sink node[5]. That is, in order for cooperating nodes to reach the sink node using CT, the following condition should hold:

$$d_{\text{req}} \leq d_{\text{tx}}^{\max}. \tag{16}$$

When using CBD for CT networks, we use d_{req} for creating the set $R_{i,d}^{N}$ for node i. That is, for Node i and a sink node, Node d, we first fix N and consider each combination of Node i's cooperators and calculate d_{req}, and if (16) holds, we add the combination to $R_{i,d}^{N}$. We do this procedure for all possible N ($1 \leq N \leq N_c^{\max} - 1$) and get the complete set of $R_{i,d}^{N}$. Based on $R_{i,d}^{N}$, $n_{i,d}^{N,k}$'s are defined. The orthogonal diversity channel is obtained by space-time-block-code (STBC) [31], and the maximum number of orthogonal channels is assumed to be four ($N_c^{\max}$=4). When calculating d_{req}, we use the path loss exponent of 2.9 and cooperative diversity gains of 7.5, 9.23, and 9.98 in dB units for N=1, 2, and 3, respectively, following [24].

In the network simulation, we assume that the storage capacity limit of a node is 5 (J), and we make the sensing tasks to be well scheduled so that each sensed data is generated in different time incurring no collision or interferences for both CT and non-CT networks. More specifically, for the kth reporting interval [$(k-1)T_{\text{RP}}$, kT_{RP}], node i senses and reports its data at $(k-1)T_{\text{RP}}$ +$(i-1)T_{\text{RP}}/N_s$, however, when the node cannot sense or report its data at this time because it does not have enough energy, it completes its sensing task as soon as it has enough energy. At time T_{serv}, no node does the sensing task because the required service time is finished.

The initial energy of each node is assumed to be 0.02 (J). We set the initial energy value to be low so that we can capture the impact of the energy harvesting earlier in the network simulations. We make the service demanding to see the upper bound of the supportable services. Because of the highly demanding service and nodes having small initial energy, we are able to detect the failure of meeting the service requirement earlier in the network simulations. Therefore, we set T_{serv}=24 hours and use it for CBD and network simulations. We consider both grid networks and randomly deployed networks. In the case of the grid

[3] We choose the E-WME algorithm because it has provably good performance (asymptotically optimal) and is specifically designed for energy harvesting networks. E-WME uses the cost metric that includes storage capacity, harvesting rate, residual energy, and energy consumption, and the least-cost route is selected.

[4] REACT assumes an existing non-CT primary routing scheme. A node on the route triggers CT by comparing its residual energy with that of the next-hop node in its primary route. If the next-hop node has less energy, the node decides to do CT; it selects cooperators based on their residual energies and their distances to the sink node.

[5] $d_{\text{req}} = (10^{D/10} \sum_{i=1}^{N_c} d_s(n_i)^{-\alpha})^{-1/\alpha}$, where n_i is the ith cooperating node, $d_s(n_i)$ is the distance between a node n_i and the sink node, α is the path loss exponent, and D is the cooperative diversity gain in dB.

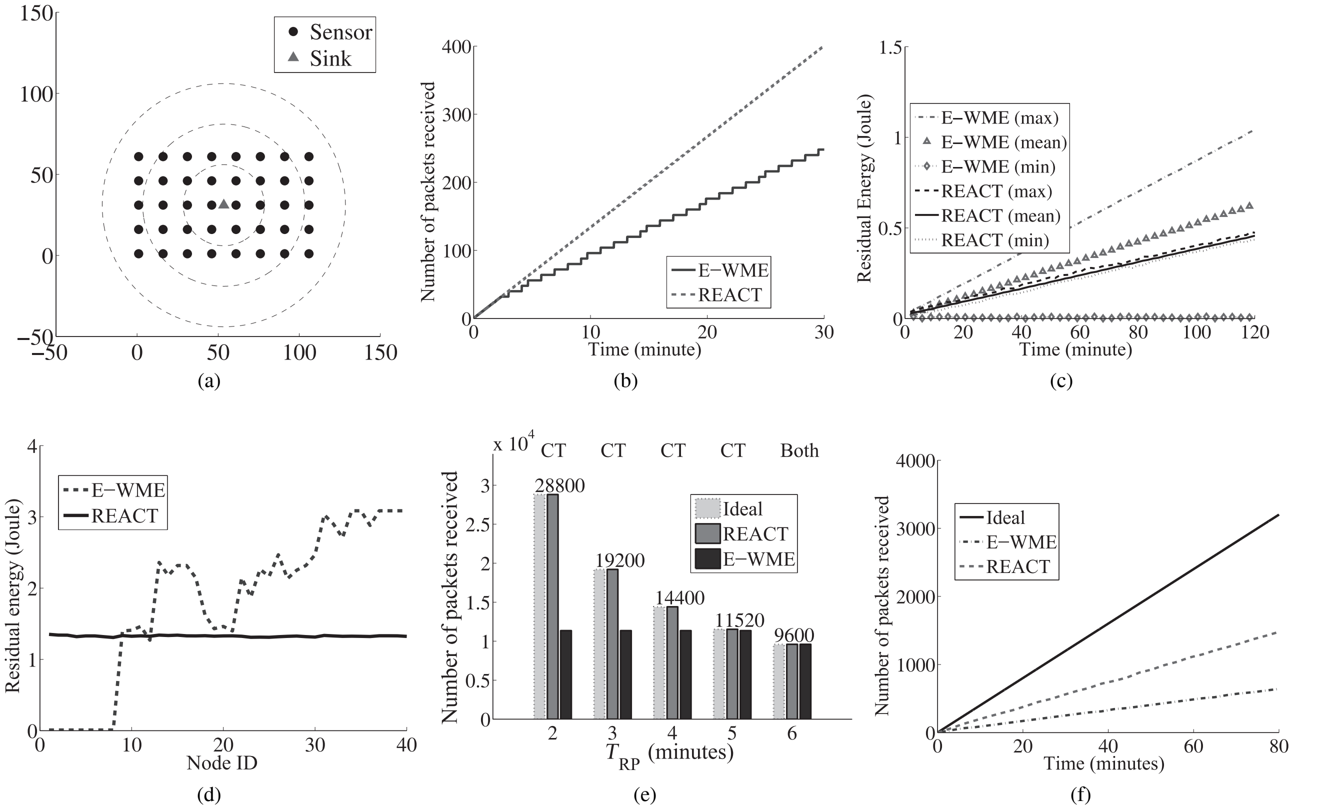


Fig. 3. Network simulation results and topology of 5x8 grid network: (a) Network topology, (b) received packets vs. time. $T_{\mathrm{RP}} = 3$ minutes, (c) residual energy vs. time. $T_{\mathrm{RP}} = 3$ minutes, (d) residual energy right after six hours. $T_{\mathrm{RP}} = 3$ minutes, (e) received packets vs. reporting period after the simulation ends, and (f) received packets vs. time. $T_{\mathrm{RP}} = 1$ minute.

networks, we consider a square-grid network with 15 m minimum node spacing and a sink node at the center of the network. For randomly deployed networks, we consider square-shaped networks with a single sink node located at the bottom center of the network. We assign the node ID of a node according to the proximity of the node to the sink node (the node closer to the sink node gets lower node ID).

We first look at the case of the constant harvesting rate. In this case, we assume that the harvesting rate is P_{EH} in Table 1, and the energy is constantly replenished. Let us first consider the 5×8 grid network shown in Fig. 3(a). The dashed circles in Fig. 3(a) indicate Levels 1-3. The network simulation results of E-WME and REACT for this network are summarized in Fig. 3.

Fig. 3(b) shows the number of packets received by the sink node over time when $T_{\mathrm{RP}} = 3$ minutes. In this case, all the sensed data from 40 nodes should be delivered to the sink node every 3 minutes, and it can be seen from Fig. 3(b) that REACT serves the network as desired, whereas E-WME cannot, which indicates that $T_{\mathrm{RP}} = 3$ minutes is too demanding for E-WME. Note that in the beginning of the simulation, E-WME and REACT have the identical performance because each node has its initial energy to spare and does not shut down in the beginning even though it overuses its energy. Fig. 3(c) shows the mean, maximum, and minimum residual energies of nodes over time. As can be seen from the figure, the residual energy averaged over the network increases for both E-WME and REACT because energy is constantly replenished, however, it can be observed that the difference between the maximum and minimum energies of E-WME is very large indicating a significant energy imbalance in the network, whereas REACT's minimum energy value is relatively large and close to the maximum value, showing a balanced energy consumption. Fig. 3(d) shows the residual energy snapshot of each node right after six hours. As can be seen from the figure, in the case of E-WME, the nodes close to the sink node (nodes with low Node IDs) have very low residual energies compared to the others. This explains the poor performance of E-WME in Fig. 3(b); the nodes close to the sink node run out of their energies frequently, and the sensed data cannot reach the sink node until those nodes replenish their energies. Fig. 3(e) shows the number of packets received by the sink node after the simulation ends for five different reporting periods. Here, an imaginary "ideal" case where any sensed data can immediately reach the sink without any delay is considered also, and the number on top of each bar group shows the value of the ideal case. For all T_{RP}'s in the figure, REACT, representing the range extension CT case, provides the same throughput results as the ideal case, whereas, in the case of E-WME, representing the non-CT case, deviates from the ideal when $T_{\mathrm{RP}} \leq 5$ indicating that non-CT cannot meet the service requirement for $T_{\mathrm{RP}} \leq 5$ (For T_{RP}=5, E-WME has the value of 11352). The residual energy trends over time for T_{RP}=2, 4, and 5, although they are omitted in Fig. 3, are all similar to the case of $T_{\mathrm{RP}} = 3$ in Fig. 3(c) where the minimum energy of REACT goes up as the time goes by and the minimum energy of E-WME is nearly zero over time. Note that observing the minimum residual energy trend over time along with the throughput result can also be used to determine the supportable services. That is, when the minimum residual energy has an increasing trend over time and the throughput behavior matches with the ideal case, we can safely conclude that the service can be supported for an infinite amount of time as long as hardware does not fail. On the other hand, we can conclude that the service cannot be supported when the network fails to match the ideal throughput and has the minimum residual energy over time that decreases to and stays around zero (as in E-WME in Fig. 3(c)). From now on, determining the supportable service using the minimum residual energy and throughput results will be referred to as the "simulation-based decision (SBD)". Using SBD, we can conclude that REACT can successfully provide the required service for $2 \leq T_{\mathrm{RP}} \leq 5$, whereas E-WME cannot.

If we are completely sure that E-WME is operating optimally for given circumstances, we can conclude that non-CT networks can only support T_{RP}=6 minutes by using SBD. To make it sure, we can use CBD, and, Fig. 3(e), in addition to simulation results, shows CBD results at the top of the graph; 'Both' indicates that both CT and non-CT can provide the service successfully, 'CT' indicates that only range extension CT can provide the required service, and 'None' (which will be used later) indicates that neither CT nor non-CT can provide the required service successfully. CBD concludes that non-CT networks can only support T_{RP}=6 minutes, whereas CT networks can support $2 \leq T_{\mathrm{RP}} \leq 5$, and these results are consistent with those of the SBD for REACT (representing CT) and E-WME (representing non-CT), which shows the usefulness of CBD in determining the supportable service of non-CT and CT networks.

From the above discussion, CT networks can have less T_{RP}, meaning that more frequent data reporting is possible for CT networks compared to non-CT networks. When $T_{\mathrm{RP}} = 1$ minute, CBD determines that neither CT nor non-CT can support required service for the network in Fig. 3(a), and the network simulation results showing the number of packets received by the sink node over time is shown in Fig. 3(f). As can be seen from the figure, both REACT and E-WME underperform the ideal case because the service ($T_{\mathrm{RP}} = 1$ minute) is too demanding. However, even in this case, the throughput of REACT is better than that of E-WME. The reason for this is that the non-CT network has to wait for the nodes that are close to the sink node to replenish their energies when the network is disconnected, whereas CT network may wait less than that because it has an option to use a VMISO link instead of using the nodes close to the sink node.

Fig. 4 shows the other benefits of using range extension CT when T_{RP} is fixed. Fig. 4(a) shows the network simulation results for different network sizes (e.g., network size of 5×7 means total 35 nodes in the network) when $T_{\mathrm{RP}} = 2$ minutes. Here, the received packet ratio, measured after simulation ends, is the ratio of the number of received packets when a certain routing protocol is used to the number of received packets of the ideal case. SBD (we omit the results of the minimum residual energy over time) concludes that REACT can support all network sizes considered in Fig. 4(a) and E-WME can only support 5×3 network, which is consistent with CBD results shown at the top of Fig. 4(a). Fig. 4(b) shows the case where we have used the harvesting rate of βP_{EH} instead of P_{EH} for 5×8 network

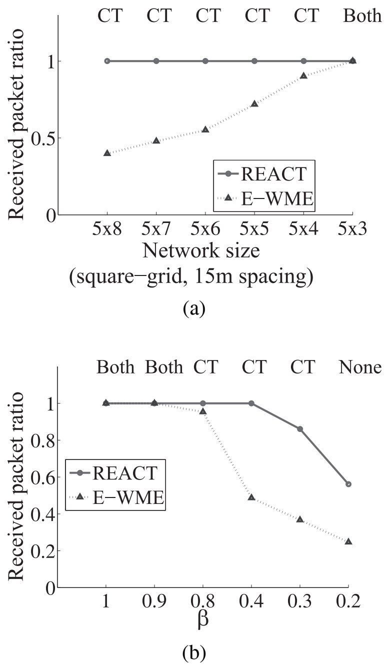


Fig. 4. The results of network simulations and CBD for grid networks: (a) Received packet ratio vs. network size. $T_{\mathrm{RP}} = 2$ minutes and (b) received packet ratio vs. β. 5×8 network. $T_{\mathrm{RP}} = 6$ minutes.

with $T_{\mathrm{RP}} = 6$ minutes, which is intended to observe the effect of poor energy harvesting environments. The simulation-based decision concludes that REACT can support as low as $\beta = 0.4$, whereas E-WME can support as low as $\beta = 0.9$ only, showing that CT can operate the network successfully in a poor energy harvesting environment (where the harvested energy is relatively weak) where non-CT cannot support. CBD determines that an optimal CT routing can support as low as $\beta = 0.3$ as shown in Fig. 4(b). This indicates that a CT routing scheme which is more appropriate than REACT may exist under given circumstances. This is not surprising because, unlike E-WME, which was designed for energy harvesting networks and proven to be asymptotically optimal, REACT was neither designed for energy harvesting networks nor proven to be optimal. Note that SBD results for E-WME are consistent with CBD results for non-CT.

The benefits of using CT are not restricted to a certain network topology. For example, we can also observe the effectiveness of using CT for randomly deployed networks. In the random deployment case, even when the same number of nodes and T_{RP} are used, the supportable service depends on how nodes are located. Therefore, we do CBD and SBD for 20 different random deployment cases given a network size and provide the results. For, 50 m×50 m with total 50 nodes (excluding the sink node) and T_{RP}=2 minutes, the non-CT network is able to support 6 cases out of 20, and, when REACT is used, the network is able to support all 20 cases considered. When we change T_{RP} to 3 minutes, the non-CT network can support 17 cases out of 20, and, using REACT can support all 20 cases considered. For, 75 m×75 m with total 60 nodes (excluding the sink node) and T_{RP}=3 minutes, the non-CT network cannot support any cases out of 20, and, when REACT is used, the network can support all cases considered. This again shows that CT networks can provide better services compared to non-CT for randomly deployed networks. For all cases that we considered for randomly deployed networks, SBD results have shown to be consistent with CBD results.

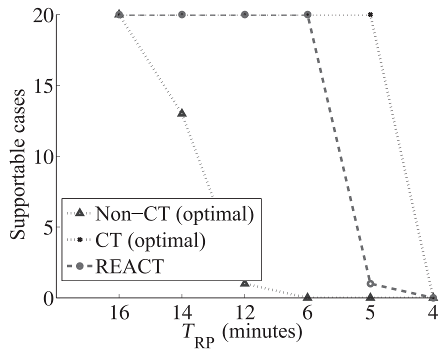
Now, we consider the case where the harvesting rate of each node is time-varying and each node has different P_{EH}'s. Since the energy source for our harvesting model is the indoor light [28], we do the following. We use a Bernoulli random variable, γ_j, with success probability of 0.5 to represent if the light is on or not in the jth minute. To model light intensity, for Node i, we generate an independent random variable, α_i, uniformly distributed over [0.5,1]. For the ith node in the jth minute, the harvesting rate is $\gamma_j \alpha_i P_{\mathrm{EH}}$. This gives the average harvesting rate of $0.375 P_{\mathrm{EH}}$, which is much less than P_{EH} of the constant harvesting rate case. The resulting overall harvested energy is also used for $T_{\mathrm{serv}} H_i$ in (13)[6]. Square-grid networks are again used, and for fixed network size and T_{RP}, we do 20 trials (20 different harvesting conditions), and, for each trial, we determine whether CT and non-CT networks can successfully support the required service or not.

Fig. 5 shows the number of cases (out of 20 cases) that the required service is determined to be supportable. The cases of optimal CT and non-CT are determined using CBD, and the case of REACT is determined using SBD. The case of E-WME is omitted here because it does not outperform the optimal non-CT case. Fig. 5(a) shows the number of supportable cases when different T_{RP}'s are used for 5×8 network. Here, when a routing scheme can support all 20 cases, we say that the scheme can "sufficiently" support the service. The optimal non-CT routing scheme can sufficiently support T_{RP}=16 minutes only, whereas REACT can sufficiently support much lower T_{RP}=6 minutes showing CT's data gathering advantage over non-CT. Note that the time-varying harvesting rate that we are considering provides much less harvested energy than the case of the constant harvesting rate we have considered earlier, and we have seen that non-CT network can support 5×8 with T_{RP}=6 minutes when the constant harvesting rate is used. This again shows that, CT network can survive using less harvested energy compared to non-CT networks. As can be seen from Fig. 5(a), CBD concludes that an optimal CT routing that can sufficiently support even T_{RP}=5 minutes may exist, however, REACT is determined to support only one case out of 20. Fig. 5(b) shows the number of supportable cases for different network sizes when T_{RP}=6 minutes, and the figure clearly shows that larger networks can be sufficiently supported for CT networks compared to non-CT networks. The network size limit for CT networks is 5×10 network, and REACT can sufficiently support 5×8 network, which is larger than 5×3 network of the optimal non-CT case.

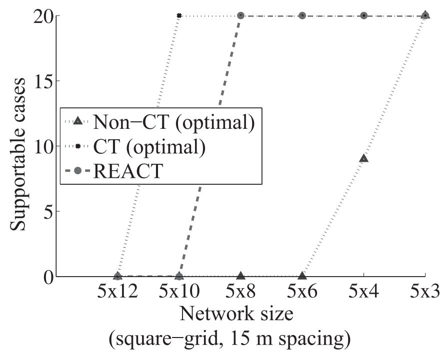
VI. CONCLUSION

In this paper, we studied the advantages of using range extension CT in multi-hop EH-WSNs. For a two-hop toy network, we have shown the possibility of using range extension CT to support more nodes and more frequent data gathering compared to non-CT. Then, we have devised a decision method that utilizes several conditions to determine the services that an optimal routing protocol can support for both CT and non-CT networks. Through evaluations of our decision method and network simulations, we showed the advantages of the CT network that use the range extension CT over non-CT, which are i) CT network can support larger networks, which provides better sensing coverage, ii) CT network can gather data more frequently, which allows one to have more up-to-date status, and iii) CT network can operate with lower harvested energy giving better chances of survival when nodes cannot harvest the expected amount of energy for some reasons.

[6]Unlike the case of the constant harvesting rate, where the harvesting rate is predictable, the amount of the harvested energy in the time-varying case is usually unknown in advance. We can use a known $T_{\mathrm{serv}} H_i$ value in (13) because CBD is for capturing the ideal case.



(a)



(b)

Fig. 5. The results of network simulations and CBD for time-varying harvesting rate. Grid networks: (a) Number of supportable cases vs. T_{RP}. 5×8 square-grid network and (b) number of supportable cases vs. network size. $T_{\mathrm{RP}} = 6$ minutes.

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