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Optimal Performance Trade-offs in MAC for Wireless Sensor Networks Powered by Heterogeneous Ambient Energy Harvesting

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***Abstract*—In wireless sensor networks powered by ambient energy harvesting (WSNs-HEAP), sensor nodes' energy harvesting rates are spatially heterogeneous and temporally variant, which impose difficulties for medium access control (MAC). In this paper, we first derive the necessary conditions under which channel utilization and fairness are optimal in a WSN-HEAP, respectively. Based on the analysis, we propose an earliest deadline first (EDF) polling MAC protocol, which regulates transmission sequence of the sensor nodes based on the spatially heterogeneous energy harvesting rates. It also mitigates temporal variations in energy harvesting rates by a prediction and update mechanism. Simulation results verify the performance trade-off predicted by our analysis for the proposed HEAP-EDF protocol. In the presence of spatial heterogeneity and temporal variations in energy harvesting rates, our proposed protocol exhibits significant performance advantages compared to the existing MAC protocols for WSNs-HEAP in the literature.**

***Index Terms*—Wireless sensor networks, ambient energy harvesting, medium access control, channel utilization, fairness, earliest deadline first.**

I. INTRODUCTION

In recent years, wireless sensor networks (WSNs) have been widely deployed for practical applications [1] because of their cost-effectiveness. However, energy remains a constraining factor in many WSN applications, because most sensor nodes in a WSN do not have cable connections to power mains.

A WSN node powered by ambient energy harvesting (HEAP) is able to operate without the need to change the battery until a hardware failure occurs. Therefore, WSN-HEAP is a suitable technology for the Internet-of-things (IoT), in which wireless communications between tags and modules are powered by batteries or super-capacitors which have limited energy capacity. WSN-HEAP is also an attractive option for large scale in-situ applications such as environment and structural health monitoring [2], in which replacing batteries regularly for WSN nodes can incur high cost.

Despite the self-sustainability and cost-effectiveness, the energy harvesting nature of WSNs-HEAP introduces new challenges. First, the harvesting rate of the same energy harvester fluctuates over time because of temporal variations in the ambient energy and hardware imperfections. Second, different sensor nodes in the same WSN-HEAP can have different energy harvesting rates, because of spatial variations of ambient energy distribution and hardware heterogeneity. Both temporal variations and spatial heterogeneity in energy harvesting rates impose difficulties in the medium access control (MAC) for WSNs-HEAP. However, to the best of our knowledge, there is a lack of studies on MAC protocols for WSNs-HEAP with spatially heterogeneous energy harvesting rates, which will be a central topic of our paper.

MAC protocols for WSNs-HEAP can be classified into contention-based [3] and polling-based [4]. As analysis [5] and simulations [6] have shown in the literature, contention-based protocols suffer faster throughput deterioration with larger network density caused by increased collision probability. In applications such as environmental monitoring and smart home/office, sensor nodes can be deployed with very high density. In such cases, polling-based protocols can deliver much better and more stable performance, as shown in [6]. Therefore, in this paper we focus our investigation on a polling-based MAC protocol for WSNs-HEAP.

The contribution of this paper is three-fold. First, we define two suitable performance metrics, namely, channel utilization and fairness, for a general WSN-HEAP in which energy harvesting rates of the sensor nodes are spatially heterogeneous and temporally variant. Afterwards, we obtain the necessary conditions for optimal channel utilization and optimal fairness, respectively, by theoretical application of task scheduling theory to the WSNs-HEAP of interest. Third, in order to achieve optimal performance trade-off, we propose a polling-based MAC protocol, HEAP-EDF, which adopts an earliest deadline first (EDF) polling policy. The proposed protocol incorporates a prediction and update mechanism to mitigate temporal variations in harvesting rates. Performance of our proposed HEAP-EDF protocol is compared with the existing polling-based and contention-based MAC protocols for WSNs-HEAP through extensive simulations. We also provide practical configuration suggestions based on our evaluations.

The rest of the paper is organized as follows. Section II summarizes the related works in the literature of MAC protocols for WSNs-HEAP. In Section III, we define key concepts and formulate the performance metrics for a polling-based WSN-HEAP. In Section IV, we illustrate the trade-off between channel utilization and fairness of the formulated system when energy harvesting rates in the same WSN are assumed to be spatially heterogeneous but temporally deterministic. Section V describes the prediction and update mechanism which mitigates the temporal fluctuations of energy harvesting rates. In Section VI, we propose an EDF-based polling MAC

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protocol, the performance of which is evaluated in Section VII through extensive simulations and comparisons. Finally, Section VIII concludes our work and points out future directions.

II. RELATED WORK

A wide range of energy conservation techniques for battery-powered WSNs have been systematically surveyed in [7] and categorized into duty cycling, data-driven, and mobility-based approaches. Energy efficiency has also been taken as a design consideration for object tracking systems [8], [9] and environmental monitoring systems [10] for battery-powered WSNs.

MAC design for WSNs-HEAP faces different challenges from those of battery-powered WSNs. The major difficulties are the spatial heterogeneity and temporal variations of ambient energy, as shown in the empirical studies in [6]. Such variations create randomness and inconsistency in energy availability for each sensor node. Various approaches have been proposed to model and predict temporal energy variations, especially for solar energy, which is the most commonly utilized environmental energy source. In [11] and [12], future energy availability is predicted with weighted-moving-average-based methods using historical energy availability data stored for the past few days, augmented with weather conditions. This approach has coarse time resolution and requires empirical data collection. In [13], it is shown that the statistical distribution of outdoor solar energy harvesting delay exhibits temporal variations during the course of the day.

Taking temporal variations of energy harvesting into consideration, both [14] and [15] investigate scheduling problems in a single energy harvesting sensor node. The former proposes a lazy-scheduling algorithm and proves its optimality for task scheduling. In the latter, energy and sensor data for a single sensor node are modeled as two separate queues in order to derive the optimal packet scheduling policy. However, these studies do not consider networks of energy harvesting nodes.

In [6], both contention-based (slotted and unslotted CSMA [3]) and polling-based (ID polling [4]) MAC protocols in conventional wireless networks have been adapted and evaluated for WSNs powered solely by ambient energy harvesting. The proposed probabilistic polling protocol, which utilizes polling packets for contention probability adjustment, has been shown to deliver the best and most stable performance overall, in terms of throughput and fairness. However, the probabilistic polling protocol in [6] does not incorporate any mechanism to update the sink node about the energy availability of each individual sensor node, which causes a lot of polling packets to be addressed to sensor nodes that have not harvested enough energy yet. In this paper, we propose a prediction and update mechanism for the time varying energy harvesting rates.

III. A POLLING-BASED WIRELESS SENSOR NETWORK POWERED BY AMBIENT ENERGY HARVESTING

We list the symbols frequently used in this paper in Table I for the ease of reference.

TABLE I
SYMBOLS USED IN THE PAPER

Symbol	Definition
α	data rate
L_p	length of a polling packet
L_d	length of a data packet
T_p	transmission duration of a polling packet
T_d	transmission duration of a data packet
T_ta	turnaround duration
T_c	duration of a polling cycle
T_n	energy harvesting delay for the n^th sensor node
$\hat{W}_n$	predicted wake-up time for the n^th sensor node
t	variable for the current time
P_tx	transmission power
P_rx	receiving power
P_ta	turnaround power
E_c	energy consumption of a polling cycle
E	variable for the current energy level of a sensor node
R	number of polling packets a sensor node is supposed to receive before going to sleep
λ_n	energy harvesting rate for the n^th node
μ	channel utilization
F	fairness
n_p	ID of the sensor node being polled
ϕ	network power balance ratio

A. Network Topology and Basic Operations

In this paper, we consider a single-hop network with a sink node and N sensor nodes. The sink node is connected to power mains and is not limited by the energy harvesting constraints. It coordinates the data packet transmissions of the sensor nodes by polling, as illustrated in Fig. 1. In order to receive a data packet from a sensor node, the sink node transmits a polling packet, which contains the ID, n_p, of the sensor node being polled. It then turns around from transmission mode to receiving mode to receive the data packet from the n_p^th sensor node. We refer to the procedure of sending a polling packet, turning around, and receiving a data packet as a polling cycle.

On the other hand, because each sensor node is powered solely by ambient energy harvesting, it can only receive the polling packet and transmit the data packet after a certain amount of energy has been harvested. After receiving a polling packet from the sink node, if it is polled, a sensor node turns around from receiving mode to transmission mode to transmit the data packet, otherwise it goes back to sleep (while harvesting energy) and wakes up to receive the next polling packet. Because the energy consumption rate of receiving is usually much higher than the energy harvesting rate, the sensor node will wake up again with a lower energy level to receive the next polling packet. Eventually, when the energy level of the sensor node falls below the amount required to transmit a data packet, it goes back to sleep until enough energy has been harvested again to receive polling packets.

In this paper we assume that a sensor node always has data packets to transmit whenever it has enough energy. This assumption is valid in many monitoring and IoT applications.

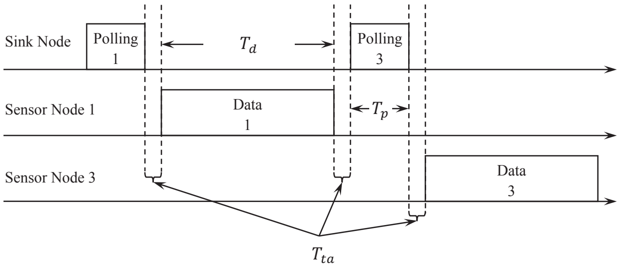


Fig. 1. Illustration of a polling-based WSN MAC protocol.

B. Timing and Energy Characteristics

Let L_{p} and L_{d} denote the length of the polling packet and the data packet, respectively. Let α denote the data rate. The transmission time for the polling packet and data packet is therefore, $T_{\text{p}} = \frac{L_{\text{p}}}{\alpha}$ and $T_{\text{d}} = \frac{L_{\text{d}}}{\alpha}$, respectively. Let T_{ta} denote the time to turnaround from transmission mode to receiving mode or vice versa. The duration, T_{c}, of a polling cycle is,

$$T_{\text{c}} = T_{\text{p}} + 2T_{\text{ta}} + T_{\text{d}}.$$

Let P_{tx} and P_{rx} denote the transmission and receiving power, respectively. The turnaround power is computed as $P_{\text{ta}} = \frac{P_{\text{tx}}+P_{\text{rx}}}{2}$. The amount of energy, E_{c}, that a sensor node needs to harvest before it can receive a polling packet is,

$$E_{\text{c}} = R \cdot P_{\text{rx}} \cdot T_{\text{p}} + P_{\text{ta}} \cdot T_{\text{ta}} + P_{\text{tx}} \cdot T_{\text{d}}, \tag{1}$$

in which $R \geq 1$ is the number of polling packets a sensor node will receive before going to sleep if not polled. Note that, R is a configurable parameter which can be adjusted to optimize energy utilization of the network, as it will be shown later. During MAC operations, the actual number of polling packets a sensor node receives, before its energy falls below the required level to transmit a data packet, may deviate from R, because of temporal variations of energy harvesting rates.

In general, energy harvesting rates of sensor nodes in the same WSN-HEAP can be both spatially heterogeneous and temporally variant. In the following discussion, we first focus on a WSN-HEAP with spatially different but temporally deterministic energy harvesting rates, in order to illustrate the trade-off between channel utilization and fairness caused by the spatial heterogeneity. We then relax the deterministic constraint and propose a mechanism which can effectively predict and update the temporal variations of energy harvesting rates, taking the spatial heterogeneity into consideration.

Let λ_n denote the energy harvesting rate for the n^{th} sensor node. The time it requires to harvest E_{c} amount of energy is,

$$T_n = \frac{E_{\text{c}}}{\lambda_n},$$

which is the energy harvesting delay for the n^{th} sensor node.

Without loss of generality, we assume that, $\lambda_1 \geq \lambda_2 \geq ... \geq \lambda_N$. Therefore, $T_1 \leq T_2 \leq ... \leq T_N$. Note that, under normal circumstances, $T_n \gg T_{\text{c}},$ for $n = 1, 2, ..., N$, due to efficiency of various practical energy harvesting technologies, including solar energy harvesters.

C. Performance Metrics

In this paper, we focus on two important performance metrics, namely, the channel utilization and the fairness in the context of a generalized WSN-HEAP.

1) Channel Utilization: Throughput is one of the most important performance metrics for a networking system. In this paper, we use the channel (time) utilization as the indication for network throughput. The channel utilization is defined as the fraction of channel time which is used to transmit data packets. In the context of our polling-based WSN-HEAP, over a time interval $[t_a, t_b],\ t_a < t_b$, if N_{tx} sensor nodes have transmitted after being polled, the channel utilization μ is computed as, $\mu = N_{\text{tx}} \cdot T_{\text{d}}/(t_b - t_a)$.

2) Fairness: Unlike the case of WSNs without HEAP constraints, the fairness metric of the WSN-HEAP must take the spatial heterogeneity of energy harvesting rates into consideration. We define a new fairness metric in this paper for WSN-HEAP consisting of sensor nodes with different energy harvesting rates. For the n^{th} sensor node itself, its own optimal channel time utilization achievable is, $\mu_{\text{opt},n} = T_{\text{d}}/T_n$, which reflects the limitation of its own energy harvesting capability.

Let the actual channel utilization be denoted as μ_n. The normalized channel utilization is, $\eta_n = \mu_n/\mu_{\text{opt},n}$. Jain's fairness metric [16] in this case is computed as,

$$F = \frac{(\sum_{n=1}^{N} \eta_n)^2}{N \sum_{n=1}^{N} \eta_n^2}.$$

Observe that, if $\forall n,\ \mu_n = \epsilon \cdot \mu_{\text{opt},n}$, for the same $0 < \epsilon \leq 1$, we have $\eta_n = \epsilon,\ \forall n$. Hence $F = 1$, corresponding to the maximum fairness based on Jain's fairness metric. Intuitively, this means that, when the channel utilization, normalized based on each node's individual energy harvesting capability, is the same for every node, fairness is maximized. Therefore, this new definition is suitable for WSNs-HEAP consisting of nodes with different harvesting rates, because it takes into consideration the individual energy harvesting capability of each sensor node.

IV. THE TRADE-OFF BETWEEN CHANNEL UTILIZATION AND FAIRNESS

After defining the performance metrics of channel utilization and fairness, we proceed to investigate their trade-off in the same WSN-HEAP in which sensor nodes have different energy harvesting rates.

A. Optimal Channel Utilization

Ideally, for the polling-based MAC protocol for WSN-HEAP discussed in this paper, the optimal channel utilization for the entire network, μ_{opt}, is achieved when every polling packet is followed by a data packet transmitted by the sensor node being polled. There should be no idle time in the channel besides the two turnaround period in each polling cycle, i.e.

$$\mu_{\text{opt}} = \frac{T_{\text{d}}}{T_{\text{p}} + 2T_{\text{ta}} + T_{\text{d}}}. \tag{2}$$

In order to achieve optimal channel utilization, a set of requirements on the energy harvesting delays, $T_n,\ n = 1,\ 2, ..., N$, and the polling cycle duration, T_c, must be satisfied. In this paper, we only focus on the necessary condition which is most relevant to the trade-off between channel utilization and fairness, namely,

Theorem 1. *To achieve optimal channel utilization, as defined in (2), for a polling-based WSN-HEAP with sensor node energy harvesting delays $T_1 \leq T_2 \leq ... \leq T_N$ and polling cycle duration T_c, we must have,*

$$\sum_{n=1}^{N} \frac{1}{T_n} \geq \frac{1}{T_c}. \tag{3}$$

Proof: Consider the N^th sensor node, which has the longest energy harvesting delay, T_N. When it has just finished transmission after being polled, it takes another $T_N - T_\mathrm{c}$ seconds for it to harvest enough energy to be polled again. For the case of optimal channel utilization, within this period of $T_N - T_\mathrm{c}$ seconds, every polling packet should be followed by a successful data packet transmission.

Obviously, $\frac{T_N - T_\mathrm{c}}{T_\mathrm{c}}$ is the upper bound of the number of polling cycles within this period of $T_N - T_\mathrm{c}$ seconds. Let k_n denote the number of times that the n^th sensor node can be polled to transmit its data packet within this period, for $n = 1,\ 2, ...,\ N - 1$, then optimal utilization requires,

$$\sum_{n=1}^{N-1} k_n \geq \frac{T_N - T_\mathrm{c}}{T_\mathrm{c}}.$$

On the other hand, each k_n is bounded by the maximum number of times the n^th sensor node can be polled within $T_N - T_\mathrm{c}$ seconds,

$$k_n \leq \frac{T_N - T_\mathrm{c}}{T_n}.$$

It follows that,

$$\sum_{n=1}^{N-1} \frac{T_N - T_\mathrm{c}}{T_n} \geq \sum_{n=1}^{N-1} k_n \geq \frac{T_N - T_\mathrm{c}}{T_\mathrm{c}}.$$

Therefore, we have,

$$\sum_{n=1}^{N} \frac{1}{T_n} = \sum_{n=1}^{N-1} \frac{1}{T_n} + \frac{1}{T_N} \geq \frac{1}{T_\mathrm{c}}.$$

■

Intuitively, the necessary condition (3) implies that the energy generation rate must be greater than or at least equal to the energy consumption rate of the WSN-HEAP in order to maintain continuous data packet transmissions.

Note that, (3) alone is only a *necessary but not sufficient condition* for the channel utilization to be optimal in all cases.

B. Optimal Fairness

In the strict sense, achieving optimal fairness requires the n^th sensor node to be polled to transmit its data packets for every T_n seconds, which is the minimum duration between two consecutive pollings of the n^th sensor node. Just as in the case of achieving optimal channel utilization, achieving optimal fairness also imposes a set of requirements on the energy harvesting delays, $T_n,\ n = 1,\ 2, ..., N$, and the polling cycle duration, T_c. Next, we first model fairness-optimized polling in WSN-HEAP as a task scheduling problem, to which we apply the theoretical results concerning task schedule feasibility [17], in order to derive the necessary condition which is relevant to the channel utilization and fairness trade-off.

Define a set of N tasks, $\tau_1,\ \tau_2, ...,\ \tau_N$, which correspond to the N sensor nodes' transmission operations. Let all the tasks have the same execution time, T_c, which corresponds to the duration of a single polling cycle. Let all the N tasks be non-preemptive because each sensor node can only transmit a data packet in an uninterrupted, continuous way.

Let the tasks be periodically released, with the n^th task's period as T_n. This corresponds to the fact that the shortest duration between two consecutive polls of the n^th sensor node is T_n. Moreover, let the deadline for the n^th task be the same as its period. A set of tasks is said to be *schedulable* if every task can be scheduled and executed before its deadline.

After establishing the correspondence between the polling-based WSN-HEAP and the set of non-preemptive periodic tasks, it is easy to see that, achieving optimal fairness for the WSN-HEAP in the strict sense, is equivalent to scheduling the corresponding set of periodic non-preemptive tasks without any deadline violations. As it has already been proven in [17] (Theorem 4.1), we directly apply the theoretical result here.

Theorem 2. *A necessary condition for the set of non-preemptive periodic tasks to be schedulable with earliest deadline first (EDF) scheduling, i.e., achieving optimal fairness for the WSN-HEAP, is*

$$\sum_{n=1}^{N} \frac{1}{T_n} \leq \frac{1}{T_c}. \tag{4}$$

Intuitively, (4) implies that the entire WSN-HEAP's energy generation rate is less than or at most equal to its energy consumption rate. Note that, this is again a *necessary but not sufficient condition* for achieving optimal fairness in all cases.

The trade-off between channel utilization and fairness for the same polling-based WSN-HEAP can be observed from both (3) and (4). Intuitively, the higher the energy generation rate in a WSN-HEAP compared to the energy consumption rate, the higher the number of sensor nodes that have harvested enough energy at any given time, and hence the easier it is to schedule their transmission without leaving idle channel time, but at the same time the more difficult it is to ensure that every sensor node can transmit immediately after it has harvested enough energy, because it may need to wait for other sensor nodes with earlier deadlines to be scheduled first. On the other hand, the lower the energy generation rate in a WSN-HEAP compared to the energy consumption rate, the lower the number of sensor nodes that have harvested enough energy at any given time, and hence the easier it is to schedule their transmission immediately after they have harvested enough energy, but the more difficult to fully utilize the channel time.

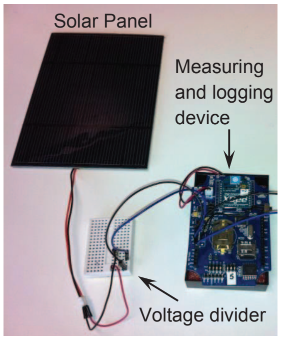


Fig. 2. Sample setup for solar energy harvesting measurement.

Therefore, the ratio between the network energy generation rate, $\sum_{n=1}^{N} \frac{E_c}{T_n}$ and the network energy consumption rate, $\frac{E_c}{T_c}$, is an important indicator of the trade-off between channel utilization and fairness in a WSN-HEAP. For the convenience of discussion, we define,

$$\phi = \sum_{n=1}^{N} \frac{T_c}{T_n},$$

as the network power balance ratio for the WSN-HEAP.

V. THE PREDICTION AND UPDATE OF ENERGY HARVESTING RATES

So far, we have assumed deterministic energy harvesting rates for the convenience of analyzing the trade-off between channel utilization and fairness. However, the energy harvesting rate of a practical harvester under a real environment experiences random temporal fluctuations. In this section, we verify the random temporal fluctuations and propose a mechanism to predict and update each sensor node's real-time energy harvesting rate.

A. *Temporal Variations of A Solar Energy Harvester*

We have chosen a commercial solar panel, namely, the Seeeduino 2 W solar panel for empirical data collection purposes. As shown in Fig. 2, after passing through a simple voltage divider circuit, the output voltage of the panels are logged by a Seeeduino Stalker board through its on-board 10 bit ADC input port. Fig. 3 shows the temporal power outputs of the solar panel in the outdoor environment under direct sun light, over a half an hour duration from 11:30 AM to 12:00 noon. It can be clearly observed that, the output voltage experiences random fluctuations over the half an hour duration. Fig. 3 also shows the corresponding autocorrelation function of the same power output from the solar panel over 2000 lags, where each lag corresponds to 0.2 seconds. It takes more than 500 lags, which corresponds to 100 seconds, for the autocorrelation value to drop below 0.2. On the other hand, with the RF and timing specifications adopted in our simulations, as shown in Table II, it takes approximately 5 seconds for a sensor node to harvest enough energy to operate over one complete polling cycle when energy harvesting rate is as low as 0.1 mW. The solar panel power output has comparatively slow variations and strong correlation temporally.

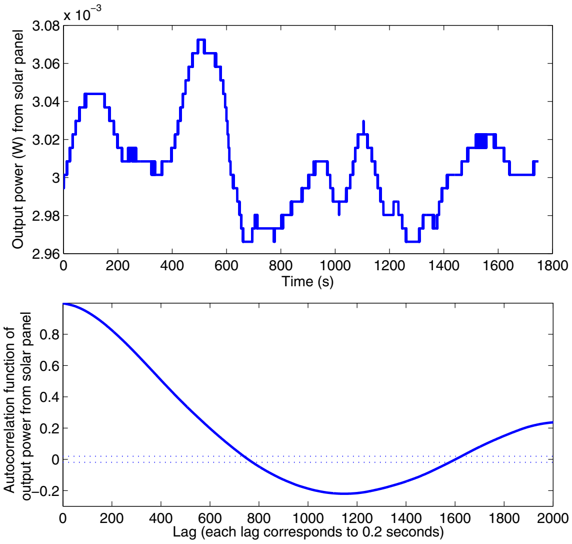


Fig. 3. Temporal variations and autocorrelation function of energy harvesting rates of a commercial solar panel over half an hour.

B. *Prediction of Energy Harvesting Rates*

Based on the observations we obtained from the outdoor solar panel output, we propose to use the linear prediction method for each sensor node to predict its own energy harvesting rate in the future, based on the current energy harvesting rates. This method is suitable for energy harvesters that have slow variations in their harvesting rates, such as solar panels and thermal energy harvesters. Note that, for energy harvesters with fast variations, more advanced techniques, such as nonlinear prediction and Monte Carlo-based methods, can be applied. The choice of prediction technique does not affect the harvesting rate update mechanism between the sensor nodes and the sink node.

Let λ_n^{k-1}, $\lambda_n^{k-2}, ..., \lambda_n^{k-J}$ denote the most recent J actual energy harvesting rates of the n^{th} sensor node, measured by itself periodically at an interval of every T_{slot} seconds. The next energy harvesting rate, λ_n^k, can be predicted by a linear model with J coefficients,

$$\hat{\lambda}_n^k = \sum_{j=1}^{J} a_j \cdot \lambda_n^{k-j}.$$

The standard method to solve the J coefficients is briefly described as follows. Let $e = \sum_{k=1}^{K} (\hat{T}_n^k - T_n^k)^2$ denote the estimation error up until the K^{th} estimate, which is to be minimized by the optimal a_j, $j = 1, 2, ..., J$. Setting $\frac{\partial e}{\partial a_j} = 0$, $j = 1, 2, ..., J$ gives J equations. The iterative Levinson-Durbin Recursion [18] method can be applied to efficiently solve for the coefficients.

When the linear prediction method is applied to our empirical data, the coefficient, a_j is very close to 1 when $j = 1$ and drops drastically to nearly 0 for $j = 2$ and onwards. This means that when the energy harvesting rates have very high correlation temporally, we can just use the most recent empirical energy harvesting rate as the estimate, which greatly reduces computational overhead.

C. *Update of Energy Harvesting Rates*

After the energy harvesting rate, $\hat{\lambda}_n$, is predicted for the n^{th} sensor node, the sensor node predict its next wake-up time, W_n, as,

$$\hat{W}_n = t + \frac{E_{\text{c}} - E}{\hat{\lambda}_n},$$

in which t is the current time and E is current energy level.

In order to update its most up-to-date estimates of energy harvesting rate, $\hat{\lambda}_n$, and next wake-up time, W_n, to the sink node, the n^{th} sensor node estimates these two parameters after it has been polled and before it transmits its data packet. In this way, the newly predicted parameters can be transmitted to the sink node in the data packet. After the data packet has been received by the sink node, the n^{th} sensor node and the sink node have established the agreement on these information. The timing computations in the MAC protocol operations therefore remain consistent between both nodes until the next update, because they are based on the same predicted data.

VI. THE EARLIEST DEADLINE FIRST POLLING MAC PROTOCOL FOR WSNS-HEAP

Based on our analysis in Section IV, we propose our HEAP-EDF protocol for WSNs-HEAP in this section.

A. *Protocol Initialization*

1) Sink Node: We assume that at the beginning of the initialization phase, the sink node *only* has knowledge of the number of sensor nodes in the WSN-HEAP. At the beginning of every T_{c} seconds, the sink node transmits a polling packet to the network. The sensor nodes are polled in a round-robin order, i.e. 1, 2,..., N, 1,..., until all the sensor nodes have responded with data packet corresponding to the polling packet addressed to each one of them.

2) Sensor Node: We assume that each sensor node starts the initialization with zero energy. After being switched on, the n^{th} sensor node starts to harvest energy. When $E_{\text{init}} = (T_{\text{c}} + T_{\text{p}}) \cdot P_{\text{rx}} + P_{\text{ta}} \cdot T_{\text{ta}} + P_{\text{tx}} \cdot T_{\text{d}}$ amount of energy has been harvested, the sensor node starts to listen on the channel for polling packets for $(T_{\text{c}} + T_{\text{p}})$ seconds. During this period, at least one polling packet will be received. Immediately after receiving the first polling packet, the n^{th} sensor node goes to sleep. If the first polling packet heard by the n^{th} sensor node is addressed to the n'^{th} sensor node, after $[(n - n' + N) \mod N] \cdot T_{\text{c}} + T_{\text{ta}}$ seconds, the n^{th} sensor node will wake up and transmit its first data packet, which also contains its predicted energy harvesting rate.

B. *Protocol Operation*

As mentioned, each time the n^{th} sensor node transmits its data packet to the sink node after being polled, it also reports two predicted parameters in the data packet header, namely, the predicted energy harvesting rate, $\hat{\lambda}_n$, and the predicted next wake-up time, $\hat{W}_n$. The sink node implementing the proposed EDF algorithm will poll the sensor node whose wake-up time is earliest. In other words, the sink node polls the n_{p}^{th} sensor node such that,

$$n_{\text{p}} = \arg\min_n \hat{W}_n.$$

TABLE II
SIMULATION PARAMETERS

Parameter	Value
N	From 10 to 100
L_{d}	160 bytes
L_{p}	20 bytes
α	250 Kbps
T_{ta}	0.192 ms
P_{tx}	83.7 mW
P_{rx}	72.6 mW
P_{ta}	78.15 mW
λ_n	From 0.1 mW to 20 mW

For an energy harvesting sensor node, the harvesting rate is usually much lower than the consumption rate for receiving/listening to channel. Therefore, even if the n^{th} sensor node goes back to sleep after receiving a polling packet which is not addressed to it, when it wakes up again to receive the next polling packet, its energy level is reduced by the amount of,

$$\Delta E = T_{\text{p}} \cdot P_{\text{rx}} - T_{\text{c}} \cdot \lambda_n.$$

Define $E_{\text{min}} = T_{\text{ta}} \cdot P_{\text{ta}} + \frac{L_{\text{d}}}{\alpha} \cdot P_{\text{tx}}$ to be the minimum energy level required to transmit a data packet. The sink node no longer considers the n^{th} sensor node, which is awake but not polled yet, as a candidate of polling, if at the time right before transmitting the polling packet, t,

$$\frac{t - \hat{W}_n}{T_{\text{c}}} \geq \frac{E_{\text{c}} - E_{\text{min}}}{\Delta E},$$

which means reception of all the previous polling packets have already reduced the energy level of the n^{th} sensor node to below the level required to transmit a data packet. At this point, the n^{th} sensor node should go back to sleep. The next wake-up time of the n^{th} sensor node will be updated as $t + \frac{E_{\text{c}} - E_{\text{min}}}{\hat{\lambda}_n}$, at the sink node.

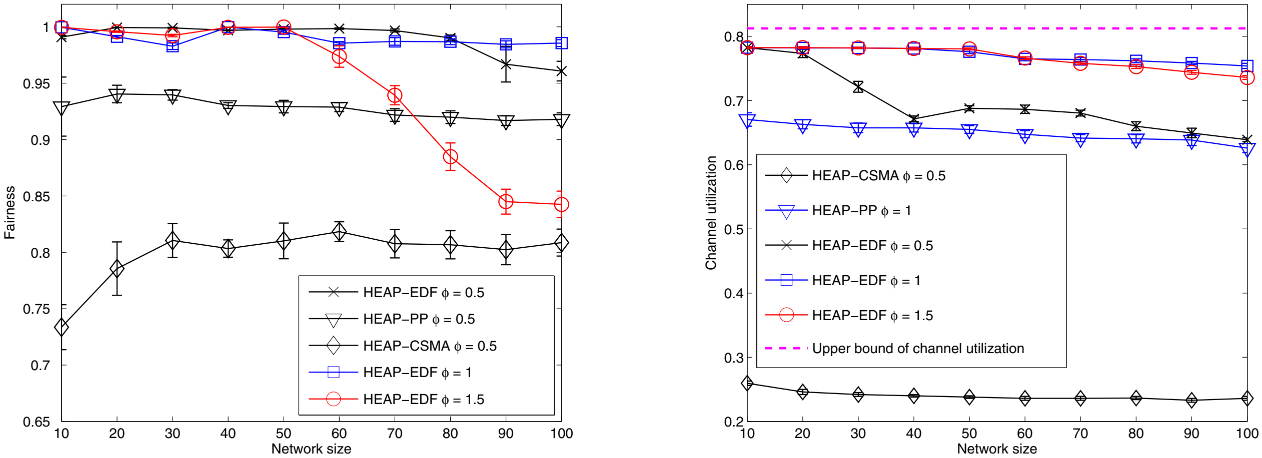
Accordingly, after transmitting a data packet, the n^{th} sensor node will wake up again at the estimated wake-up time $\hat{W}_n$, regardless of whether the energy level E_{c} is reached or not, in order to honor its previous agreement with the sink node. After having just received the $\lfloor \frac{E_{\text{c}} - E_{\text{min}}}{\Delta E} \rfloor^{\text{th}}$ polling packet at time t, if it is still not polled, it goes back to sleep and updates its next wake-up time as $t + T_{\text{c}} - T_{\text{p}} + \frac{E_{\text{c}} - E_{\text{min}}}{\hat{\lambda}_n}$.

Note that, after receiving a polling packet corrupted by link error, a sensor node will behave as if it is not polled. On the other hand, after receiving a data packet corrupted by link error, a sink node will continue to poll the next sensor node with the earliest wake-up time.

VII. SIMULATIONS AND DISCUSSIONS

A. *Simulation Setup and Scenarios*

In order to verify the performance trade-off between channel utilization and fairness of the proposed EDF-based polling MAC protocol for WSNs-HEAP, we implement the proposed protocol in the Qualnet 5.0 network simulator. A single-hop



(a) Fairness vs. network size.

(b) Channel utilization vs. network size.

Fig. 4. Fairness and channel utilization vs. network size for different ϕ, when $R = 15$.

network consisting of one sink node, connected to power mains, and N energy harvesting sensor nodes is simulated. In each simulation trial, the sensor nodes are deployed at uniformly random locations over a 50 m by 50 m area, in the center of which sits the sink node.

As listed in Table II, we set data packet size and polling packet size to 160 and 20 bytes, respectively. The data rate is 250 Kbps and the turnaround time is 0.192 ms, as specified in the IEEE 802.15.4 standard. The transmission, receiving, and turnaround power consumption rates are computed based on the specifications of a commercial RF module, CC2500, taking into consideration the typical micro-controller power consumption. Note that, we assume that the power consumption of sensing operations in a sensor node to be independent from that of networking operations. Therefore, sensing power consumption is not included in our simulations.

B. *Simulating Heterogeneous Energy Harvesting Rates*

Coexistence of sensor nodes with different energy harvesting rates in the same WSN-HEAP is a central topic of this paper. Therefore, we characterize each simulation scenario by two parameters, namely, the network size, N and the network power balance ratio, ϕ. For each simulation scenario, 10 trials are conducted. Each data point in the figures shows the average of these 10 trials with 95% confidence interval. In each trial of a scenario characterized by N and ϕ, we generate N uniformly random values, λ_n, $n = 1, 2, ..., N$ in the range of $[0.1\ \text{mW},\ 20.0\ \text{mW}]$ as the temporal average of energy harvesting rates of the sensor nodes in this trial, so that,

$$\sum_{n=1}^{N} \frac{T_c}{\frac{E_c}{\lambda_n}} \in [\phi - 0.05,\ \phi + 0.05].$$

The temporal variation of the n^{th} sensor node's energy harvesting rate is simulated by a first-order autoregressive (AR(1)) model, such that, the mean of the energy harvesting rate during the simulation time is λ_n, while the variance of the energy harvesting rate is set based on our experimental measurements.

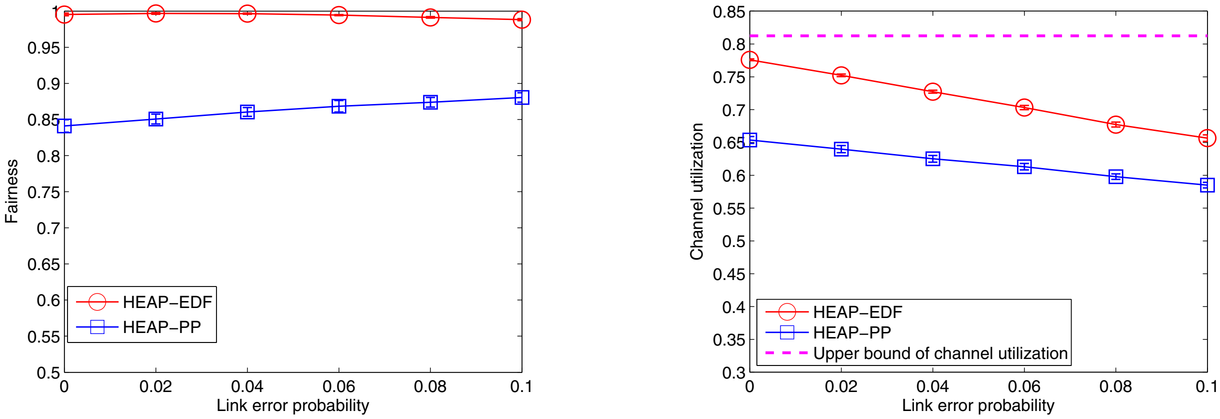
C. *Performance Trade-offs*

We first study the performance of our proposed HEAP-EDF protocol when the network power balance ratio, ϕ equals to 0.5, 1, and 1.5, respectively. For each ϕ value, we obtain simulation results with the network size, N, varying from 10 to 100, with a step size of 10. We set the energy level E_c so that a sensor node receives 15 polling packets before it goes back to sleep if not polled ($R = 15$). For comparison and benchmark purpose, simulation results are also obtained in each simulation trial for the probabilistic polling protocol (HEAP-PP) and the contention-based unslotted CSMA protocol (HEAP-CSMA), as proposed in [6]. The simulation results are shown in Fig. 4.

Note that, HEAP-CSMA delivers both the best channel utilization and the best fairness when $\phi = 0.5$. HEAP-PP delivers the best fairness when $\phi = 0.5$ and the best channel utilization when $\phi = 1$, respectively. For the clarity of presentation, we only show the results for the two benchmark protocols under these conditions when they perform the best. Performance of our proposed HEAP-EDF protocol under all cases ($\phi = 0.5,\ 1,\ 1.5$) are shown to better illustrate the trade-off.

As shown in Fig. 4(a), when $\phi = 0.5$ and the necessary condition for optimized fairness is satisfied, the proposed protocol indeed achieves best fairness performance overall, compared to HEAP-EDF with larger ϕ, HEAP-PP, and HEAP-CSMA. Because the necessary condition for optimized channel utilization is not satisfied, channel utilization is lowest for HEAP-EDF in this case. However, it is still higher than the other two protocols under the same scenario.

In the case when $\phi = 1.5$, because the necessary condition for optimized fairness is not satisfied, the overall fairness of the proposed HEAP-EDF is significantly poorer, especially when the number of sensor nodes in the network increases. This



(a) Fairness vs. link error probability.

(b) Channel utilization vs. link error probability.

Fig. 5. Fairness and channel utilization vs. link error probability when $\phi = 1$ and $R = 15$

is because when the network energy generation rate is larger than the consumption rate, at any time more sensor nodes are ready to be polled if the network size grows larger, which results in longer waiting time for each sensor node before it can be polled. The longer waiting time causes longer intervals at which each sensor node updates its own energy harvesting rate to the sink node. MAC operations and computations are based on outdated and hence inaccurate data because of the temporal variations in energy harvesting rates. Therefore, the channel utilization when $\phi = 1.5$ is also observably worse than that of $\phi = 1$, as shown in Fig. 4(b), even though the necessary condition for optimized channel utilization is satisfied.

The best overall performance is delivered by the proposed HEAP-EDF protocol when $\phi = 1$. In this case, the necessary conditions for both optimal channel utilization and optimal fairness are closely observed at the same time. As shown in Fig. 4(a), the fairness of the proposed protocol in this case is approximately the same as that of $\phi = 0.5$ and significantly higher than those of HEAP-PP and HEAP-CSMA. Fig. 4(b) shows the advantage in channel utilization of the proposed protocol. Compared with that of HEAP-PP and HEAP-CSMA, it is much closer to the upper limit of channel utilization.

Note that, HEAP-CSMA is observed to have much worse performance in both channel utilization and fairness, compared to the two polling-based protocols. This is because HEAP-CSMA is entirely a distributed protocol without any sink-sensor coordination. The spatially heterogeneous energy harvesting rates further deteriorate its performance. On the other hand, sink nodes in the two polling-based protocols explicitly (HEAP-EDF) or implicitly (HEAP-PP) coordinate the transmission in the WSN-HEAP at the node (HEAP-EDF) or network (HEAP-PP) level.

D. *Effects of Link Errors*

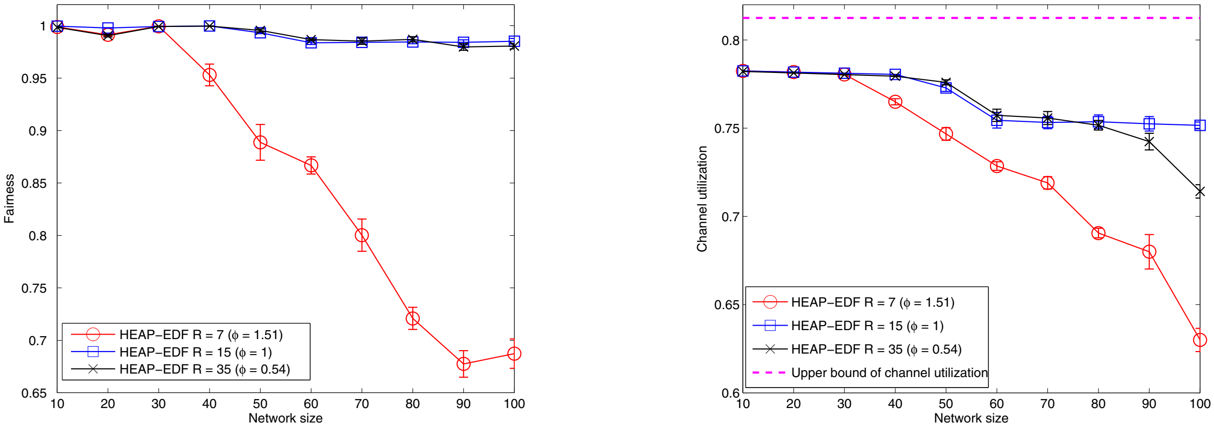
Fig. 5(a) and Fig. 5(b) show the variations of fairness and channel utilization of the proposed protocol, when the wireless link error probability is varied from 0 to 0.1, with a step size of 0.02. The values of ϕ and R are set to be 1 and 15, respectively. It can be clearly seen that, although both fairness and channel utilization suffer observable performance degradation caused by the increasing link error probability, the performance advantage of our proposed HEAP-EDF is still significant compared with that of the HEAP-PP.

E. *Effects of R*

We observe from (1) that, the amount of energy, E_c, which a sensor node must harvest before it can wake up and receive polling packet, increases linearly with increasing R, which is the number of polling packets a sensor node receives before it goes back to sleep without being polled. With given energy harvesting rates in a certain deployment plan, ϕ increases/decreases when R decreases/increases. In order to examine the effects of R, we fix the energy harvesting rates, λ_1, λ_2, ..., λ_N, and vary R in each simulation trial. The corresponding fairness and channel utilization performance are shown in Fig. 6(a) and Fig. 6(b) for different R. We observe that, when $R = 7$, $\phi = 1.51$. The proposed protocol delivers poor performance in both channel utilization and fairness. As discussed previously, it is caused by the unfulfilled necessary condition for optimal fairness, as well as the prediction error as a result of excessive waiting time before each sensor node is polled. On the other hand, when $R = 35$, $\phi = 0.54$. The proposed protocol delivers optimized fairness as the necessary condition of optimized fairness is satisfied (better channel utilization is also observed in this case). When R is set to 15, which results in $\phi = 1$, both fairness and channel utilization are optimized. These results suggest that, in practical deployment scenarios, adjusting R is an effective way to obtain desirable ϕ, in order to optimize both fairness and channel utilization. Note that, in scenarios where $R = 1$ but $\phi \ll 1$, more sensor nodes can be added to the WSN-HEAP in order to push ϕ towards 1.

VIII. CONCLUSION AND FUTURE WORK

In this paper, we formulate a generalized WSN-HEAP in which energy harvesting rates are spatially heterogeneous and temporally variant. We then analyze the optimal trade-off



(a) Fairness vs. network size.

(b) Channel utilization vs. network size.

Fig. 6. Fairness and channel utilization vs. network size for HEAP-EDF with different R

between channel utilization and fairness for such a WSN-HEAP. We propose an EDF-based polling MAC protocol, utilizing a prediction and update mechanism for energy harvesting rates across the network. Extensive simulations have verified the performance advantage of the proposed protocol compared to the existing methods in the literature. The trade-offs between channel utilization and fairness have also been verified, which provides useful insights for practical WSNs-HEAP configuration.

We point out two future directions. First, in our current study, the effects of varying some energy harvesting conditions (e.g., λ) and network configurations (e.g., R) are observed through simulations. We aim to develop a more extensive theoretical framework to study asymptotic performance bounds under these varying conditions and configurations. Second, our current investigation is limited to the single-hop network scenario. Extension to the multi-hop scenario will make the proposed protocol more applicable to large scale deployment.

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