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Energy Synchronized Transmission Control for Energy-harvesting Sensor Networks

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Abstract: Energy harvesting and recharging techniques have been regarded as a promising solution to ensure sustained operations of wireless sensor networks for long-term applications. To deal with the diversity of energy harvesting and constrained energy storage capability, sensor nodes in such applications usually work in a duty-cycled mode. Consequently, the sleep latency brought by duty-cycled operation is becoming the main challenge. In this work, we study the energy synchronization control problem for such sustainable sensor networks. Intuitively, energy-rich nodes can increase their transmission power in order to improve network performance, while energy-poor nodes can lower transmission power to conserve its precious energy resource. In particular, we propose an energy synchronized transmission control scheme (ESTC) by which each node adaptively selects suitable power levels and data forwarders according to its available energy and traffic load. Based on the large-scale simulations, we validate that our design can improve system performance under different network settings comparing with common uniform transmission power control strategy. Specially, ESTC can enable the perpetual operations of nodes without sacrificing the network lifetime.
Keywords: Wireless sensor networks, Energy harvest, Transmission control.

1 Introduction

The advance of energy harvesting and recharging techniques makes it is feasible to build long-term sensor networks for cyber-physical applications [1, 2]. In such energy-harvesting networks, sensor node with extended functional units can continuously extract energy from ambient environment, such as solar power, wind energy resource, motion and wireless charging. Although energy-harvesting sensor networks can obtain renewable energy, they impose several challenges. Energy harvesting opportunities and rate are highly environmental-dependent, and usually related to the spatiotemporal distribution of sensor nodes. For example, in solar-powered networks, the harvested energy may vary significantly with node position (e.g. under the sun or shadow) or weather patterns (e.g. cloudy or sunny). Moreover, the energy storage units, such as batteries or capacitors are limited in power capacity and have been shown to be leakage-prone [8]. Therefore, it is impossible to operate the sensors at full duty-cycle even in such energy-replenishing networks.

In consideration of harvested energy, the existing power management solutions have been widely exploited in wireless sensor networks [3, 7, 9, 10]. These approaches can be classified into two categories, one is dynamic duty-cycle scheduling schemes [3, 10], which are based on assumption that the working period of nodes could be scheduled to meet the requirement of data forwarding. However, the work schedule in many scenarios is often dependent on the application requirements, such as sensing coverage and tracking delay [11]. The other kind is focused on the energy-aware routing [7, 9, 11]. All these schemes can optimize the network performance under their supposed application scenarios.

In this paper, we study the efficient utilization of harvested energy from the perspective of transmission power control. Our motivation is quite straightforward. We observe that the increasing of transmission power can be beneficial to improving network performance, such as packet delivery ratio and delay. Meanwhile, the transmission power is directly associated with energy consumption of data transmission. Thus, we introduce the transmission power control to improve network performance while guaranteeing the sustainability in energy-harvesting sensor networks. Specifically, we propose Energy Synchronized Transmission Control scheme (ESTC), a middle layer between application and network layer. With ESTC, each node can adaptively adjust its transmission power based on its energy-harvesting capability and traffic overload. ESTC can be seamlessly integrated with current routing algorithms so that different optimization objectives can be achieved. We also present a backoff approach to avoid transmission collision among concurrent data forwarding.

Our major contributions of this work are summarized as follows. We first describes energy-harvesting sensor nodes and the duty cycle model. To balance the delivery delay and energy efficiency, we propose a distributed energy synchronized transmission control approach to find the best power level for each forwarder without sacrificing network lifetime. At last, we perform extensive large-scale simulations to validate the proposed scheme. Working with different routing policies, the simulation results show that ESTC can: i) reduce end-to-end delivery delay; ii) synchronize the energy consumption among different sensor nodes; iii) balance the traffic load to increase the node lifetime.

The rest of the paper is organized as follows: Section 2 briefly presents the related work. The concrete design of our scheme is discussed in Section 3 and the simulation results are presented in Section 4. Section 5 concludes the paper.

2 Related Work

There are two research fields related to our design: energy harvesting techniques and transmission power control.

Recently, energy harvesting and recharging technologies have been developed to ensure the sustainability of sensor networks. Many motes or platforms are designed to collect and storage these energy from environment [8]. To fully utilize the replenished energy, different power management [11] and duty-cycle based schemes [3] have been proposed. Kansal et al. [11] have proposed temporal-based approaches to adjust the duty-cycle of sensor node in order to optimize the network performance. In [10], Gu et al. first put forward the concept of energy synchronization communication, by which each node adaptively adjusts its own active instances according to the available energy budget so that the cross-delay over node can be minimized. Challen et al. [9] present IDEA, an integrated energy-aware architecture to address the energy dynamic issue of sensor nodes. In particular, they propose a holistic architecture to trade off energy objective function and other application-defined utility, such as low power listening, energy aware routing and distributed localization. In [4], Guo et al. study the joint problem of mobile data gathering and wireless charge. Differing from above schemes, their motivation is to study the mobility scheduling for efficient energy recharging and data collection. In the direction of low-duty-cycle networks, many recent works have been proposed to reduce the delivery delay for different traffic patterns. Gu et al. [17] suggest that the communication delay could be bounded with the duty-cycle adjustment of sensor nodes. Besides the delay optimization, Liu et al. [12] study the joint routing and sleep-scheduling problem, which has been proved a non-convex problem. They transform it into equivalent sigmoidal program by relaxing the flow constraints and then solve it with iterative geometric programming.

Transmission power control techniques have been widely used to optimize network performance in wireless networks. In particular, most of them are focused on the topology control [13]. Wattenhofer et al. [13] proposed a location-based, distributed topology control algorithm to balance the network connectivity and the network lifetime. At first, each node starts a neighbor-discovery process with a lower transmission range and then gradually increases its transmission radius until either one node is found in each cone of given degree or the maximum transmission power is reached. Then, a redundant edge removal process is performed in order to reduce the nodes degree and thus increase network throughput. In [6], Cheng et al. study the throughput optimization problem with transmission power control in sensor networks. They propose algorithms in order to minimize the total transmission power and total interference. Based on various link models, both computing algorithms and heuristics are discussed for the purpose of throughput maximization. In [14], Cotuk et al. analyze the impact of varied transmission power control strategies on network lifetime. Specially, they study the effect of power levels discretization on energy consumption, which is significant for practical research because the levels of transmission power are usually discrete in reality. In [15], Fan et al. propose a delay-bounded transmission power control scheme for the performance optimization in low-duty-cycle sensor network. Under the given delay bound, a cross-layer transmission power control approach is presented so that all data delivery could be achieved with minimum energy cost. In [5], Berbakov et al. consider the similar application scenario as our design. However, their goal is to find the optimal power allocation in order to maximize the total throughput within given deadline. They also assume that the storage capacity of sensor nodes is infinite and the leakage effect is negligible.

However, none of works have considered the utilization of transmission control strategy to achieve performance improvement in sustainable sensor networks.

3 Energy Synchronized Transmission Control with Harvested Energy

In this section, we present the design of energy synchronized transmission control algorithm.

3.1 Network Model

We assume a sensor network with N energy-harvesting nodes, each of them has a fixed number of discrete transmission power levels, i.e., $p_i, (1 \leq i \leq k)$, where k is the maximum number of adjustable transmission power levels. Figure 1 illustrates the configuration of energy-harvesting node, which replenishes energy from surrounding environments, receives data packets and delivers them to the sink at possible transmission power level.

Also, we suppose that all nodes are scheduled to work in a duty-cycled mode. As shown in Figure 2, a sensor node is in either active state or a dormant state. When a node is in the active state, it can transmit or receive packets from neighboring nodes. While a node is in the dormant state, it turns off all function modules except a timer to wake itself up. For successful communication, the sender should be aware of the time slots and have to wait for its receiver to wake up before it can send a packet. We define *sleep latency*, $s_{ij}(t)$ as the time interval from the moment the sender i has a packet ready to be sent at time t to the moment that the receiver j is in the active state. Without loss of generality, we suppose T is the common working period of the whole network, which can be further divided into a number of time slots with equal length. To simplify, the length of time slot is appropriate for a round-trip transmission time, τ. Based on such assumptions, the working schedule, Γ_i for node i can be uniquely represented as a set of active time slots, i.e., $\Gamma_i = \{t_1^i, t_2^i, ..., t_K^i\}$, where K is the number of time slots that the node is in the active state. For example, the work schedule in Figure 2 is $\{2, 6, 8\}$.

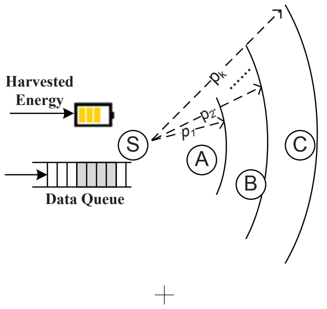


Figure 1: Energy-harvesting node.

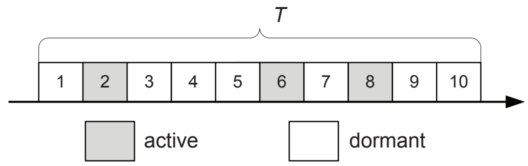


Figure 2: Working schedule.

In our design, it assumes that all node know the schedule of its one-hop neighbors. Sleep latency is the main component of delivery delay in such energy-harvesting networks.

3.2 Design Objectives

Given k available power levels, the sender have k options to relay the data packets in its data queue. We take energy harvesting into consideration and look into the following issue: *what's the optimal transmission control policy with harvested energy?* Generally, it is necessary for node to consider three aspects for such transmission decision.

- Energy budget: In general, the sender can select larger transmission power levels to reduce the sleep latency while it has enough energy budget. On the contrary, it should lower down transmission power to save energy. As shown in Figure 1, node A may increase its transmission power in order to reduce sleep latency if it has additional energy supply.

- Traffic load: Obviously, the traffic load has a significant impact on the transmission decision. More energy supply is needed when there are more data packets to be delivered in the data queue.

- Routing metric: Given transmission power, there are usually multiple potential forwarders available for current node. However, different routing metrics are designed for varied objectives. For example, the delay is the main issue to be addressed in duty-cycled sensor networks.

If there is no energy constraint, we can select the maximum available transmission power for each node in order to obtain the minimized end-to-end delay. However, such a naive and uniform transmission power control policy can waste precious energy resources and incur more transmission interference and collision. Take the dynamics of energy, traffic overload and routing strategies into consideration, our design goals include:

- **Delay Optimization.** In real world, sensor nodes are deployed to monitor or response emergency surveillance. Instead of hard deadline, our protocol provides an adaptive transmission control approach to reduce delivery delay.

- **Energy synchronization.** In energy-harvesting sensor network, each node has different energy-gathering and storage capability. Taking energy leakage into account, it is important to synchronize the demand with energy supply. In other words, we tend to consume as much energy as possible while providing the sustainability of network.

- **Balancing Traffic Overload.** Differing from wired network, the bandwidth and energy are constrained resources in sensor networks. Therefore, it is important to perform data delivery over multiple forwarding paths from source nodes to the destination. Our protocol dynamically switches forwarding among various potential forwarders according to routing metrics.

- **Localized Behavior.** It is important to keep the protocol as scalable as possible since the global coordination among hundreds of nodes may incur more energy consumption. Therefore, all behavior of our protocol are localized to achieve high scalability and low overhead.

- **Transmission Collision Avoidance.** Transmission interference and collision may happen when multiple nodes within transmission range try to send packets simultaneously. It is necessary to introduce the corresponding mechanism to reduce such collision.

3.3 Protocol Architecture

In this section, we propose an energy synchronized transmission control scheme (ESTC) which adaptively selects the optimal transmission power at transmission layer and diverts traffic overload through different forwarders at network layer in order to improve network performance with the extra harvested energy. In specific, our protocol includes the following components.

- ESTC module.

- Energy estimation module.

- Delay estimation module.

As shown in Figure 3, ESTC is the kernel module, which is responsible for the selection of approximate transmission power level and next-hop forwarder. The data queue in upper layer is holding all data packets to be relayed. Assuming all data packets have the same size, the traffic overload can be represented as the length of data queue. Energy and delay estimation are two modules that help ESTC to make the forwarding decision. In other word, ESTC will select the transmission power level and corresponding forwarder according to the available energy and feedback from neighboring nodes. The detail of these modules is discussed in the following sections.

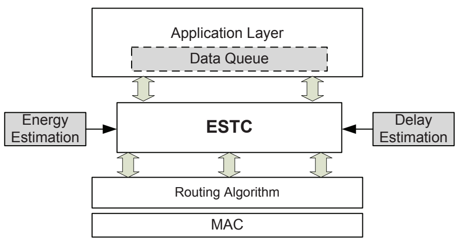


Figure 3: ESTC Architecture.

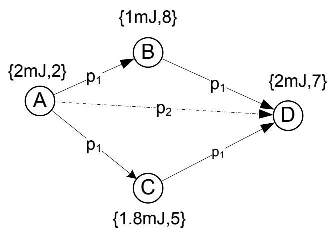


Figure 4: Example of Energy and Delay Estimation

3.4 Energy Estimation

To carry on energy synchronized communication, it is significant to know the amount of energy that can support data delivery. In sustainable sensor networks, the harvested energy is usually unpredictable and changes significantly over time [8]. Energy estimation module traces both energy load as well as the harvesting rate on a node. Let the battery level for node s at the time t_0 be $B_s(t_0)$, a common model to estimate the available energy at time t_1 is:

$$B_s(t_1) = B_s(t_0) + \int_{t_0}^{t_1} H(t)d_t - \int_{t_0}^{t_1} L(t)d_t \tag{1}$$

Here, $H(t)$ and $L(t)$ are the energy harvesting rate and consuming rate at time t. Other models, such as online assess model in [16] can also be used, but they are usually focused on specific harvesting platforms, for example, the supercapacitor-powered sensor node. Instead, we assume a general in-site model by reading the energy value in the later simulations.

Notice that, the primary objective of our design is to pursue the network sustainability, which can be represented as the network lifespan. To prolong the network lifetime, it is required to balance the energy consumption among sensor nodes. In short, the issue is how much energy can be used for each node without compromising the network lifetime? Assuming the remaining energy of the network is known a prior, we can formally define the energy availability of given node.

Definition 1. ***(Energy Availability).*** Available energy of node s, B_s^a is the extra energy which can be used for data delivery but without reducing the network lifetime. Assuming the average energy of the network ($B\prime$) is known a prior, we have $B_s^a = B_i(t) - B\prime(t)$, where $B_i(t)$ is the remaining energy of node at time t.

However, it is usually inefficient to update the average energy level of the whole network from time to time. One possible solution is to approximate the average energy with the energy load of ancestor nodes. As shown in Figure 4, node A, B, C can forward their data packets to the sink via node D and their remaining energies are 2mJ, 1mJ and 1.8mJ, respectively. Accordingly, the available energy for node D is the difference between its own energy and the average value, i.e., 0.4mJ. One may argue that we can use the lowest energy level (1mJ of node B) as the baseline. However, we do not assume a fixed transmission power and forwarding path. That is, node A may switch to node C or even increase transmission power to reach node D directly for the energy-efficiency. Obviously, it is not accurate to take the minimum residual energy as the reference energy.

Maintaining the accuracy of energy estimation requires periodical exchange of these information. In practice, piggybacking on the normal data traffic can be used to reduce this control overhead. When a node receives message from its ancestor, it will recalculate the average energy value and then put it into the header of data packet. In such way, each node can trace the available energy of the network.

3.5 Fitting Routing Algorithms

With given transmission power p_i, there may be multiple available candidates for data forwarding in sensor networks. In this section, we will show how ESTC works with various routing metrics, such as link-quality-based routing (ETX) [18], delay-based routing (DESS) [19] and power-aware routing (PAR) [22]. To be scalable, it assumes that all routing decisions are made based on the local information.

Link-quality-based Routing

ETX is a link-quality-based routing algorithm, in which the expected transmission count is taken as routing metric. The one-hop ETX is the average number of transmission required to send a packet over a link, which is usually described as the reciprocal of link quality. However, wireless link is often extremely unreliable in the real environment. The pair-wise link qualities, described as the packets reception ratio (PRR) could be very different under varied transmission power. In practice, link quality is usually evaluated by periodically broadcasting probe messages as that in [10], which is a little energy-consuming in our design due to the adjustable transmission powers.

On the other hand, reception signal strength indicator (RSSI) has a close relationship with PRR according to the empirical results [20]. Specifically, there is a clear threshold for RSSI to achieve a nearly perfect link quality. To save energy, we use the RSSI instead of PRR as the metric to filter qualified forwarding candidates. Generally, a higher transmission power tends to bring better link quality [20]. In detail, the sender periodically monitors the received signal strength from its one-hop neighbors and then evaluates their RSSIs. For given transmission power, we can select the candidate with the strongest RSSI as next hop.

Delay-based Routing

In duty-cycled sensor network, sleep latency is often in the order of seconds, while propagation delay and processing delay (in the order of milliseconds) can be ignored. Therefore, it is necessary to estimate the sleep latency. Assuming each node is assigned a predefined work schedule, we can calculate the sleep latency by the waiting time from the ready time to the moment that it is sent out. To do that, each node only needs to share its work schedule with their neighboring nodes. In a resource-constrained environment, it is energy-consuming and non-scalable to estimate the end-to-end delay among different sender-receiver pairs. Instead, we use one-hop delay value as the evaluation metric.

In ideal network with perfect link, one-hop delay can be represented as $s_{ij} = (t_j - t_i)$, where t_j, t_i are the wake-up time of transmission pair. For example, the sleep latency from node A to B in Figure 4 is 8-2=6. Notice that, the end-to-end delay is also related to the length of forwarding path. To model such parameter, we present the one-hop relative delay, d_{ij} as,

$$d_{ij} = s_{ij} * \frac{D_j}{D_i}. \tag{2}$$

Here, D_j, D_i are the distances from the sender and next-hop to the destination, respectively. Assuming two candidates wake up at the same time, the nearer one would be selected as next hop. In real scenario with unreliable links, we can evaluate delivery delay according to the model proposed in [21].

Energy-based Routing

In ESTC, the selection of transmission power is from the view of sending node. However, it is possible to integrate ESTC with power-aware routing algorithm in order to maximize energy efficiency and network lifetime [22]. To do that, each node can periodically collect energy information from its one-hop neighbors and make the forwarding decision in time. In specific, we select the metric aiming at maximizing the lifetime of all nodes. As a result, the neighboring node with maximum consumed energy for each packet would be selected as the potential forwarder. Similar as link-quality-based routing, the sender exchanges the statistical information with its neighbors, including residual energy, queue size so that the optimal forwarder could be chosen. Taking Figure 4 as an example, if the lengths of their queue are the same, node C instead of node B would be selected since it has more residual energy.

3.6 Collision Avoidance

Though there is low data traffic in duty-cycled sensor networks, it is possible that multiple transmissions among neighboring nodes are collided when transmission power is increased. Meanwhile, the concurrent transmission happens only when their receivers wake up at the same time. To resolve the conflicts, we introduce transmission-power-based backoff approach. When a node intends to begin a transmission, it first backs off for a period of time at the begin of a slot. The duration of the backoff depends on the power level used in the transmission. The higher the transmission power, the shorter the back off duration. When multiple nodes within communication range decide to send packets, they back off first before transmission and the one with highest power level starts first. Other nodes listen to the channel first after the backing-off time. Once catching the ongoing transmission, they will abort their own transmission and insert the data packet with updated timestamp into the data queue.

Suppose the backoff time bound is T_b and the maximum number of concurrent transmissions is C, we can divide T_b into C slots for different backoff durations. A sender can compute its backoff duration t_b with the following equation.

$$t_b = \lfloor C(1 - \frac{i}{k}) \rfloor \frac{T_b}{C} + X, 1 \leq i \leq k. \tag{3}$$

where i is the number of transmission power level and X is a random number generated from $[-\frac{T_b}{C}, +\frac{T_b}{C}]$ if $i \leq k$ and from $[0, +\frac{T_b}{C}]$ if $i == k$. This ensures that the backoff time is positive and within the backoff bound. The random period can reduce the chance of collisions when two or more nodes use the same power level. By using such backoff method, we avoid conflicts but also save energy since the transmission with higher power level starting early can be heard by more potential senders.

3.7 Energy Synchronized Transmission Control (ESTC) Scheme

Based on the energy estimation and routing algorithm, ESTC protocol can make the approximate forwarding decision. The detailed process of transmission power decision is described in Algorithm 5.

To efficiently synchronize the harvested energy, ESTC takes an energy adaptive strategy based on the feedback of energy estimation and real-time traffic load. If there is no additional energy budget, the current node sends the packet with minimum transmission power level. Otherwise, the sender can increase its transmission power in order to support the packet delivery in data queue. Our first step is to decide the amount of energy that can be used by the data delivery per packet. Assuming that each packet has the same length, the energy consumption for data delivery is only dependent on the used transmission power. In other word, the sender can calculate the energy consumption for given transmission power level. Given the frame size of data packet (F) and the data rate (r), we can compute the energy consumption of data transmission, E_i by given transmission power p_i with the following equation.

$$E_i = P_i * \frac{F}{r}. \tag{4}$$

Here, P_i is the power consumption for given transmission power level p_i, which is usually dependent on the wireless radio. Next, we can decide the appropriate transmission power level by comparing E_i with the available energy (See Line 1-9).

With the selected transmission power, ESTC sends packet in the order of data queue according to the given routing policy (See Line 10-16). Since data packets can only be delivered when the next-hop forwarder wake up in duty-cycled sensor network, the data queue in upper layer is holding data packets generated by current node or received from the other nodes. Each data packet includes the following fields, (ID, TimeStamp, TransmissionTimes). To prioritize the delay, we suppose all data packets are stored in the order of their generated time. For example, it needs to forward data packets via the earliest wake-up node with DESS. If the transmission succeeds, it would update the available energy and fetch the next packet from data queue. Otherwise, ESTC inserts the failed packet into the data queue and waits for the next schedule. The packet would be dropped if it is out of the maximum allowable transmissions ($TransmissionTimes$). Notice that, the above algorithm is locally executed at the individual node, which is completely distributed.

ALGORITHM 1: Energy Synchronized Transmission Control at time t

Require: the number of packets in data queue, n;
Require: the average energy of ancestor nodes, $B\prime$;
Require: the amount of remaining energy, B_i;
Require: the maximum number of concurrent transmissions, C;
Require: the routing algorithm, $routingPolicy$;
Require: the backoff time bound, T_b;

$p_a \leftarrow p_1$;
$B_s \leftarrow B_i(t) - B\prime(t)/n$;
for all transmission power $p_i \in [p_1, p_k]$ **do**
    $E_i \leftarrow P_i * \frac{F}{r}$;
    if $(E_i > B_s^a)$ **then**
        break;
    end if
    $p_a \leftarrow p_i$;
end for
if (routingPolicy is ETX) **then**
    select next hop (n_h) according to link quality;
else if (routingPolicy is DESS) **then**
    select next hop (n_h) according to sleep latency;
else if (routingPolicy is PAR) **then**
    select next hop (n_h) according to energy level;
end if
for $i = 0$ to k **do**
    if $(i == k)$ **then**
        $X \leftarrow rand(0, +\frac{T_b}{C})$;
    else if $(i < k)$ **then**
        $X \leftarrow rand(-\frac{T_b}{C}, +\frac{T_b}{C})$;
    end if
end for
$t_b \leftarrow \lfloor C(1 - \frac{i}{k}) \rfloor \frac{T_b}{C} + X$;
Back off the time, t_b.
Fetch and send packet to n_h with power level p_a.

4 Performance Evaluation

In this section, we validate the performance of energy synchronized transmission power control scheme. In specific, we assume a data collection scenario consisting of energy-harvesting sensor nodes, which is a common communication pattern. Source nodes periodically sense and generate data packets, then deliver them to the sink node through multi-hop forwarding path. Due to energy efficiency, all nodes except the sink are presumed to work with low-duty-cycle mode.

4.1 Baseline and Selection of Routing Algorithms

To verify the effectiveness of our design, we compare ESTC scheme with those that do not use energy synchronization mechanism, i.e., the uniform transmission power control (termed UTPC later). To verify our design, the ESTC is integrated with the various routing algorithms.

- Link-quality-based: ETX [18] is proposed to minimize the expected transmission count for multi-hop data communication.
- Delay-based: DESS [19] is presented in order to minimize delivery delay for duty-cycled sensor networks.
- Power-Aware-Metric: PAR [22] is proposed to minimize the energy consumption and then prolong the network lifetime. In our experiment, we take the relative energy budget as routing metric.

Notice that, all routing algorithms can be easily integrated with our design. For given transmission power, each node selects the corresponding candidate according to the above routing metrics.

4.2 Simulation Setup

We assume that all sensor nodes are randomly deployed in a $200m \times 200m$ square field, where 40 nodes are selected as data source and the sink is located in the right corner of sensor area. The average data rate of source node is 2 packets with frame size 64B for each working period. Without otherwise specified, we set radio parameters strictly according to the CC2420 radio hardware specification [23]. In detail, we select 8 typical transmission power levels, -25dBm, -15dBm, -10dBm, -7dBm, -5dBm, -3dBm, -1dBm, 0dBm indexed from level 0 to level 7. The energy model is identical to the practical measures of CC2420, i.e., the corresponding transmission power ranges from 29.04mW to 57.42mW. The energy consumption of data reception is 62mW.

Each experiment is repeated 30 times with different deployments and working schedules generated by random seed. For each experimental setting, the result is averaged over 100 source-to-sink communications under given network size and density. To emulate the energy-harvesting environment, each node is supposed to increase its energy resource at a stochastic charging rate.

In the simulation, three performance metrics are evaluated: i) the E2E delivery delay, defined as the total time spend for the delivery of a packet; ii) the energy efficiency, defined as the standard deviation of remaining energy for all nodes within the network; iii) the network lifetime, defined as the number of time slots from the beginning to the time when first node is running out of its energy. We have to mention that it is a dynamic concept in energy-harvesting network, only representing the current status of network. With the replenishment of energy, the dying nodes can refresh and join the data forwarding again.

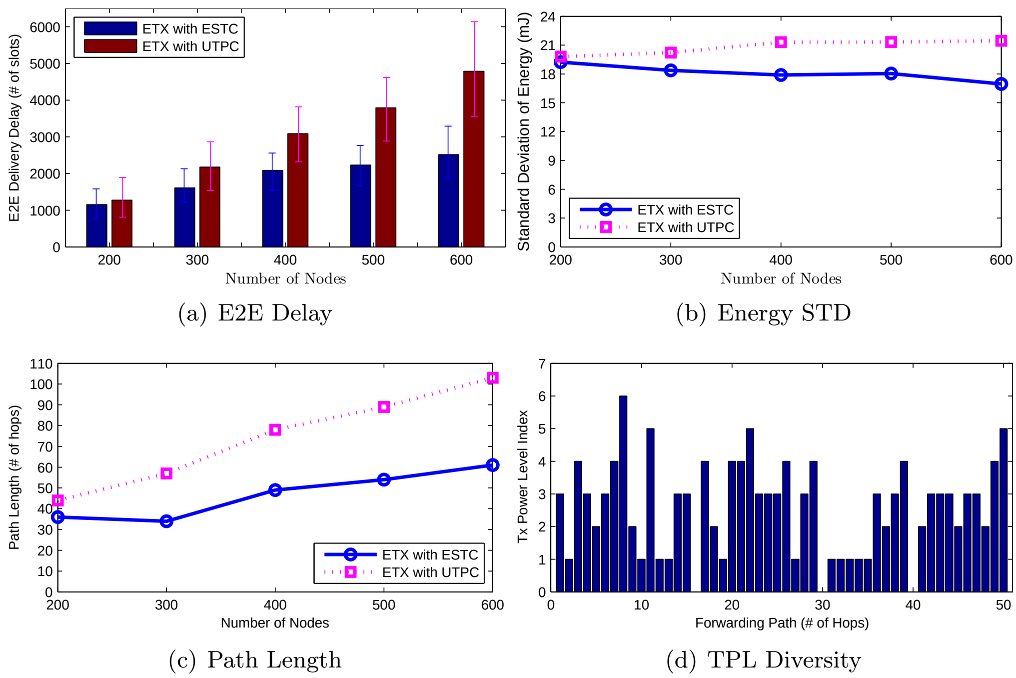
4.3 Performance Evaluation

This section evaluates the E2E delivery delay, energy consumption and network lifetime for different schemes. Moreover, we compare ESTC and UTPC scheme under varied network settings.

Working with ETX

In this section, we first study the delivery delay of both ESTC and UTPC while the number of nodes changes from 200 to 600. As can clearly be seen from Figure 5(a), ESTC has a smaller delay than UTPC under all node densities. For example, ESTC reduces the E2E delay by 47% compared with UTPC when the number of nodes is 600. It can also observed that the delay for ETX-based schemes increases with the number of nodes. More nodes are deployed in the network, more potential candidates are available. On the other hand, those candidates near to the sender are more likely selected, leading to a longer data forwarding path for ETX-based forwarding. To verify, we plot the the forwarding length of both schemes in Figure 5(c), which shows the average length of both ESTC and UTPC is increasing with nodes density. More importantly, the average length of ESTC is much shorter than UTPC in all cases. For example, the maximized length for UPTC is 103 while the corresponding length for ESTC is 61.

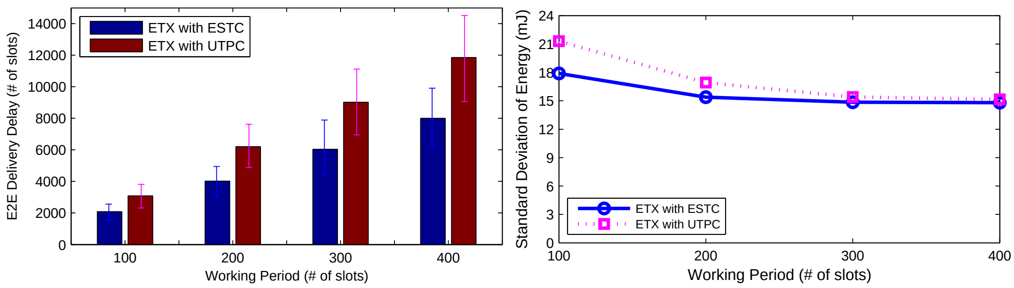
Figure 5(b) shows that ESTC has smaller standard deviation of energy than UTPC, representing that nodes with ESTC has more balanced energy consumption in the process of data collection. The reason is that ESTC tends to distribute the energy consumption among different nodes by adjusting the transmission power. We plot the transmission power levels (TPLs) used in the data forwarding process of ESTC as Figure5(d). It can be clearly seen that nodes with ESTC can adaptively select transmission power according to the availability of energy resource and link quality. From the figure, it is observed that many nodes select very low transmission power, such as level 0 or 1 in dense deployed area. Notice that, UTPC tends to select the same transmission power for all data delivery, resulting in higher energy consumption.



(a) E2E Delay (b) Energy STD

(c) Path Length (d) TPL Diversity

Figure 6: Impact of Node Density for ETX.



(a) E2E Delay (b) Energy STD

Figure 7: Impact of Duty Cycle for ETX.

Figure 6(a) shows the impact of working period on network performance, where the E2E delivery delay increases with the working period. This is because the duty cycle is reduced while the working period increases, leading to the prolong of sleep latency per hop. For energy efficiency, we observe the similar result that the energy dissipation among nodes is more balanced for ESTC than UTPC as Figure 6(b).

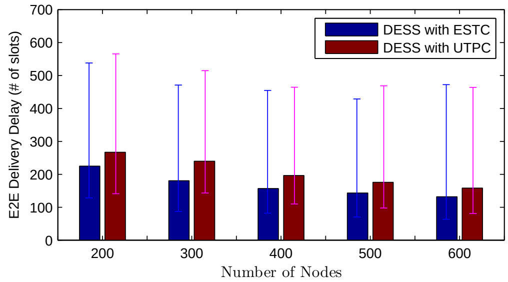
Working with DESS

In this section, we study the network performance of both ESTC and UTPC working with DESS. Again, ESTC has a smaller delay than UTPC for DESS under all node densities. Figure 7(a) shows that the delay for DESS-based scheme decreases as node density, in which more potential candidates with earlier wake-up schedule are provided. Moreover, DESS-based schemes have much lower delays compared with those ETX-based schemes. For instance, the average E2E delay for DESS is around 200 under all node densities. On the contrary, the value for ETX is more than 1000 as shown in Figure 5(a). The rationale behind is that DESS prioritizes the delivery delay since each node always selects the earliest wake-up neighbor to forward data packets. The other reason is that the path length for DESS routing is much shorter than ETX as shown in Figure 7(c). Similarly, ESTC outperforms UTPC on energy efficiency due to the adjusting of transmission power levels as shown in Figure 7(b).

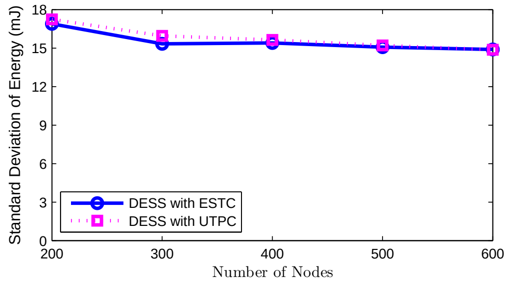
Figure 8(a) shows the average delay under different working periods. We can see that the delivery delay increases with the working period of nodes. For example, the average E2E delay increases from 156 to 573 for ESTC. Totally, with energy synchronization, ESTC can reduce delivery delay by 20% than UTPC under all working periods. Figure 8(b) shows the energy efficiency under varied duty cycles, which proves the slight superiority of ESTC over UTPC. The main reason is that the schedule of nodes is assumed to be fixed in the whole lifetime so that the same node is usually selected as the forwarder in multiple times. On the other hand, the total energy consumption for DESS-based approach is much less than ETX-based scheme due to shorter forwarding path.

Working with PAR

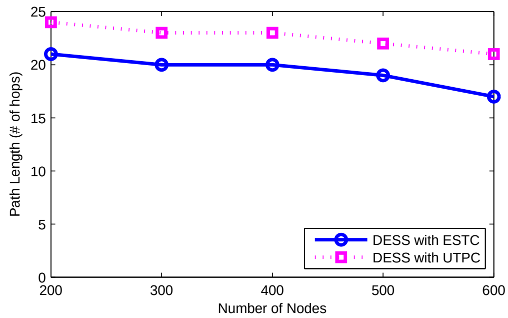
In this section, we study the network performance of proposed schemes with power-aware routing algorithm. In the simulation, we assume that each node can harvest energy within predefined period and then measure the network lifetime. In special, the average charging rate of nodes is set from 0 to 3. Figure 9(a) shows that ESTC can maintain longer lifetime than UTPC under all energy charging rates. Notice that, the network lifetime with energy-harvesting capability is much longer than that of static sensor network. For example, the network lifetime lasts 3.7 million of slots with average charge rate 3, around 9 times of the lifespan when there is



(a) E2E Delay

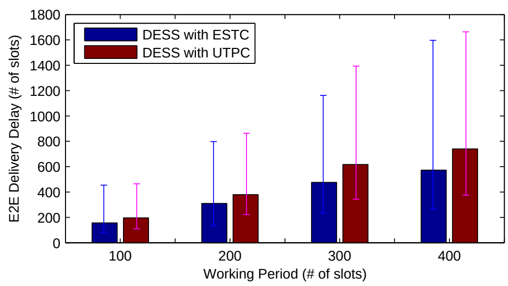


(b) Energy STD

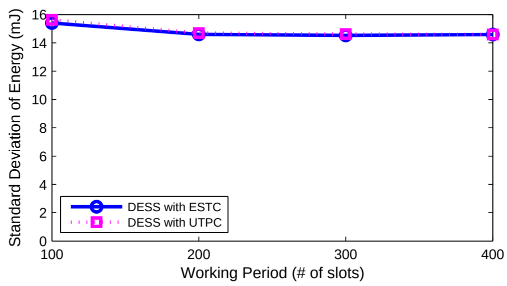


(c) Path Length

Figure 8: Impact of Node Density for DESS.

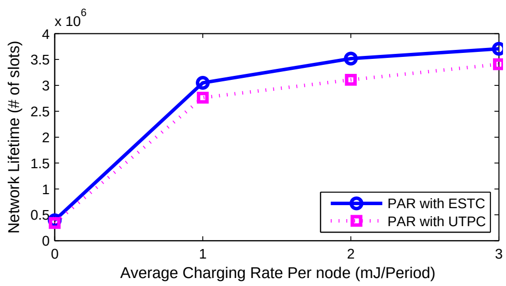


(a) E2E Delay

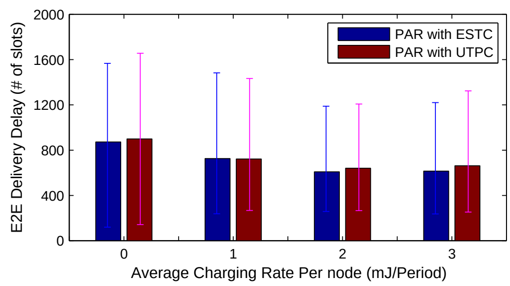


(b) Energy STD

Figure 9: Impact of Duty Cycle for DESS.



(a) Network Lifetime



(b) E2E Delay

Figure 10: Impact of Charging Rate for PAR.

no extra harvested energy. Also, we deploy the E2E delay for both UTPC and ESTC in Figure 9(b), which demonstrates ESTC can still reduce the delivery delay even working with the power aware routing policy. In fact, when the packet is delivered along with an energy-rich path, it is more likely to be transmitted at high power level, leading to a lower sleep latency.

5 Conclusion

Harvesting energy technique provides opportunities for the substantiality of resource-constrained sensor networks. To efficiently utilize the harvested energy, we propose energy synchronization transmission control scheme which can work together with different routing strategies. In specific, ESTC adaptively selects the suitable transmission power according to the energy availability and traffic load in order to reduce delay and balance the energy consumption. We verify the effectiveness of our design by conducting large-scale simulations, showing that ESTC can reduce delivery delay and energy consumption without compromising network lifespan compared with uniform transmission power control design.

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