Delay Bounded Maintenance Scheme in Rechargeable Wireless Sensor Networks

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Abstract—In rechargeable wireless sensor networks, owing to the current energy conversion technology limitations, the energy harvested from surrounding environment usually is not enough to continually power sensor nodes. Therefore, the nodes have to operate in a very low duty cycle, which means nodes have to activate shortly and stay in the sleep state most of the time in order to recharge the energy. On the other hand, due to sporadic availability of energy, nodes must adjust their duty cycles continuously. Hence, packet delivery latency is critical in rechargeable WSNs.
In this work, we introduce an active instance augmented scheme and provide an algorithm for finding the minimal sleep latency from a node to the sink by augmenting minimal h active instances. For bounding E2E delay from source node to the sink in the network, we propose an E2E delay maintenance solution. Through extensive simulation and experiments, we demonstrate our delay bound maintenance scheme is efficient to provide E2E delay guarantees in rechargeable wireless sensor networks.

Index Terms—Wireless sensor networks; delay bounded; rechargeable-WSNs

I. Introduction

Wireless sensor networks (WSNs) are comprised of a large number of low-cost, low-power, small size, and multi-functional sensor nodes with finite battery life that can sense and process data and communicate with each other over a short distance. They are usually deployed in remote or dangerous areas that render servicing impossible or impractical. This means sensor nodes must operate for a long period of time in order to be useful. To this end, in recent years, researchers have paid much attention to WSNs have been a topic of much interest to researchers due to their wide-ranging applications. For example, they have been used in military applications, environmental applications, health applications and home applications [1], [2], etc.

A fundamental problem in WSNs is the limited lifetime of sensor nodes. To this end, a significant amount of work has been carried out across the protocol stack to prolong the lifetime of WSNs. Examples of which include energy-efficient Medium Access Control (MAC) protocols, duty-cycling strategies, energy efficient routing and topology control mechanisms [3], [4]. An interesting approach to extend the lifetime of sensor nodes is to equip them with rechargeable technologies that convert sources such as body heat, foot strike, and finger strokes into electricity. Assuming energy neutral operation [5], a sensor node can operate perpetually if the harvested energy is used at an appropriate rate. Note, a harvesting node is said to achieve energy-neutral operation if the energy used is always less than the energy harvested and the desired performance level can be supported in a given harvesting environment.

In these so called energy harvesting or Rechargeable WSNs (R-WSNs), although their lifetime is less of an issue, the available energy on nodes varies dramatically over time owing to the varying environment conditions. For example, a node that relies on the sun will extract more energy on sunny days as compared to when it is cloudy and extract no energy at night at all. For instance, when a node lies in direct sunlight, the energy harvesting rate can reach 15000 $\mu W/cm^2$, while during cloudy days, the energy harvesting rate only reaches 150 $\mu W/cm^2$[6]. Given these characteristics, nodes must regulate their activities accordingly to ensure energy neutral operation.

To regulate energy consumption, nodes adapt their duty cycle according to available energy or application requirements. For example, in bursty and high traffic load scenarios, the duty cycle of nodes can be increased to meet QoS requirements, such as low latency and high reliability [7]. That is, nodes wake-up more frequently to reduce end-to-end delays. The tradeoff here is that a high duty cycle leads to significant energy expenditure. Hence, duty cycles of around 1-10% are typical in order to maximize energy saving and minimize latency [8]. The mechanisms used to adapt the duty cycle of nodes are significantly different to those used in conventional WSNs. Due to environmental factors that lead to sporadic availability of energy, a node must adjust its duty cycle continuously.

Duty cycling leads to high packet delivery latency or sleep delay [9]. Sleep latency is the duration from the moment a packet is ready at the sender to the moment the destined receiver accepts the packet [10]. The key contributor to delay is the fact that if a node wants to communicate with a neighboring node, it has to wait for the corresponding neighbor to wake up. Sleep latency is usually in the order of seconds, which is much longer than other delivery latencies, such as, processing delay, transmission delay, and propagation delay. The End-to-

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End (E2E) latency is the sum of sleep latencies along the path of data delivery.

In many applications, E2E latency guarantee is required for sink-to-sources and sources-to-sink scenarios. For example, sources will have to actively communicate with the sink in order to inform it of sensed data so that in turn the sink can issue new commands [11], [12]. In these operations, an E2E delay bound is usually required. Henceforth, in this paper, we address the delay bound problem. Specifically, we seek to reduce the delay of all E2E paths using the least amount of energy expenditure. In a nutshell, we propose a distributed Active Instance Augmentation (AIA) algorithm to bind the E2E delay for sink to sources, and sources-to-sink communications in R-WSNs. To the best of our knowledge, this is the first generic work that studies the use of AIA to bound delays in r-WSNs.

The remainder of this paper is organized as follows. In section II we present a number of existing E2E latency guarantee solutions, while in section III specify the network model and assumption, Section IV we present our method and design. Section V contains experimental results. Conclusions are presented in section VI

II. Related Work

Dynamic duty cycle schemes are widely adopted to lower latencies in WSNs. Demand Wakeup MAC (DW-MAC) [8] introduces a low-overhead scheduling algorithm that allows nodes to wake up on demand during the sleep period as traffic load increases, which allows DW-MAC to achieve low latency delivery. Adaptive Scheduling MAC (AS-MAC) [13] allows nodes to dynamically change the length of the awake duration in each operation cycle and be adaptive to variable traffic load, which enabling AS-MAC to resiliently schedule data transmission in the sleep period to reduce E2E delay. Lu *et al*. [14] show that E2E delay can be reduced significantly by carefully choosing multiple wake-up slots for each node given a duty cycle budget in tree and ring topologies. Wang *et al*. [15] propose DutyCon, a control theory-based dynamic duty cycle control approach, which decomposes the end to end delay guarantee problem into a set of single hop delay guarantee problems along each data flow in the network. In DutyCon, the author control the single hop delay of each packet to meet the delay requirement by dynamically adjusting the receiver's sleep interval. These schemes encounter critical tradeoffs between network lifetime and data delivery latency. In r-WSNs, the lifetime is not the main problem which can be maximized by operating in an energy neutral mode for nodes.

By considering the dynamical energy supply for sensor nodes, Noh *et al*. introduce a duty-cycle-based low-latency geographic routing for asynchronous r-WSNs [16]. They propose D-APOLLO, an algorithm that periodically selects appropriate duty cycle of each node to achieve minimum latency, which base on the currently estimated energy by predicting energy consumption and energy expected from harvesting device. Sun *et al*. [17] present an algorithm to reduce delivery delay that lets a sensor with packets to be sent dynamically selects a forwarder from a forwarding sequence set, in which potential forwarders are sorted in the order of their wake-up time. Gu *et al*. [18] introduce a method to increase duty cycle by strategically adding wake-up slots to nodes to reduce end-to-end delay to within a given bound. Gu *et al*. [19] further to present Energy Synchronized Communication (ESC) to synchronize the harvested energy at an individual node to minimize communication delays by shuffling and adjusting the working schedule of a node under different rates of energy harvest further. However, more energy will be consumed and collision will be serious in these protocols.

Different from earlier works, which either focus on static battery-powered network or minimizing delay under energy constraints, in this work, we present a delay maintenance algorithm satisfying E2E delay bound by augmenting active instances of nodes in R-WSNs. In summary, on observing the lack of dynamic energy supplement consideration for bounding communication delay in existing power management protocols, we introduce the first generic delay maintenance algorithm with active instance augmentation in R-WSNs.

III. System Model

In this section, we will define the network model and elaborate on the packet delivery process related to our E2E delay maintenance design. In addition, we define sleep latency in R-WSNs and some assumptions used in this work.

Consider a static rechargeable wireless sensor network modelled as an undirected graph $G=(V,A)$, where V is the set of n rechargeable sensor nodes and sink nodes within the network. A is the set of links and A= $\{A \mid (i,j)\in A, i\in V, j\in V\}$. G consists of a finite nonempty vertex set V and edge set A of ordered pairs of distinct vertices of V. At any point of time t, there are two states for any sensor node with duty-cycle: active and dormant. In active state, a sensor node can generate data after sensing its surrounding environment, transmit the data to its neighbors or receive data from its neighbors. When a sensor node is in the dormant state, it turns off all its modules except for a timer to wake itself up. Two nodes i and j are connected by a link if and only if they can transmit packets to each other with a transmission power less than the maximum transmission power at each node and the receiver is in active state. Thus all links are assumed to be bi-directional. We assume that the network graph is connected, i.e. There is always a path between any pair of nodes i and j in V.

The working time of all sensor nodes are divided into periodic working schedules and every node shares its schedule with its neighbors. The packet delivery is affected by the working schedules of nodes. The working schedule consists of a set of active instances, during which a sensor node can transmit and receive packets. The transmitting and receiving activity happen in the active state. There are two situations for a dormant sensor node to wake up. The node has packets to transmit to its neighboring nodes or it is scheduled to the active state when its battery is recharged enough to support this activity. In other words, a sensor node can wake up to transmit a packet at any time only if its receiver is in the active state, but can receive a packet only when it is in the active state itself. Since a sensor node can only receive packets during its active state, therefore the time a sensor node receive packets is the same as active instance in its working schedule.

For all sensor nodes, since their neighbouring nodes switch between active and dormant states regularly, therefore, the transmission between a pair of nodes becomes time-dependent strictly. In the paper, let the duration of periodic working schedules be T which can be divided into a sequence of time instances with length t. The duration of t is the unit of working time in an activity. In other words, for a node, when it is in active state within period time T, its working schedules can be represented by a set of time instances including one or multiple time instances with length t. Essentially, if we let t be the finest granularity of time durations in the time instance designation, we can represent any node working schedule with the fixed t.

For the purpose of explaining the active and dormant activities utilizing the working schedule and time instance, let T_i denotes the working schedule of node i, t_i denotes the time instance that node i is in active state which can be called an active instance for node i. Therefore, we can have $T_i = \{t_1, t_2, \ldots, t_n\}$ for node i when it is in active state for working schedule T_i. For instance, a sensor node i with a period duration time $10\,t$ and working schedule $T_i = \{2,3,5,8,9\}$, as is shown in Fig.1. Therefore, in the period of time $T_i = \{2,3,5,\ 8,9\}$, the sensor node is in active state and in dormant state in remains time of the duration.

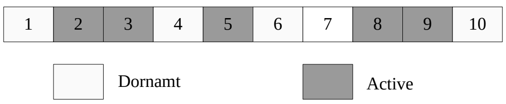

Figure. 1. Example of working schedule.

In R-WSNs, the duty cycle scheme is utilized widely to meet the requirements for sensor nodes to recharge their batteries, therefore, the sender have to wait for its receiver switch to active state before it can send a packet. Hence, in the process of data transmission between a pair of neighboring nodes, sleep latency is the main factor for causing E2E delay problem of R-WSNs, especially when sensor nodes are in low duty cycle which means sensor nodes are in dormant state in most of the time in order to recharge the battery.

To further illustrate the concept of sleep latency, Fig2 shows an example of four sensor nodes in the liner network. The working schedule for four sensor nodes a, b, c, d be $T_a = \{2\}$, $T_b = \{3\}$, $T_c = \{9\}$ and $T_d = \{6\}$. It means the sensor node b will be in active sate and can receive a packet from its neighboring node in time 3. If the sensor node a has received a packet in time 2 and ready to send the packet to its neighboring node b at next time, the sleep latency for the first attempted transmission from node a to node b therefore is $d_{ab}(2,3)$ =1. The E2E delay is $d_{ad}(2,9)$ =14 from node a to node b.

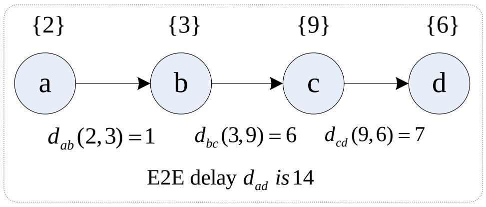

Figure. 2. Four nodes with working schedule in a linear network.

Based on the network model, we make several assumptions. These assumptions are affected by practical design, such as time synchronization and packet delivery.

We assume the transmitting power of a sensor node is controllable, which means transmitting power can be modulated according to the transmitting distance and remain energy of sensor node. The area that a sensor node can sense depends on the battery energy of node which has been recharged in the past time. A sensor node has a biggest transmitting distance when its battery energy is full. The storage of battery depends on the material and technology which is not considered in our paper. When a sensor node has full energy, it stops to recharge energy and switch to dormant state. The switching between active sate and dormant state is according to the working schedule.

In R-WSNs, a sensor node in the network will adjust its duty cycle continuously and keep a very low duty cycle in most of time, therefore the synchronous schemes is of higher efficiency than asynchronous schemes for packets delivery. Hence, the synchronous schemes are utilized for network synchronization in our works. After a sensor node join in the networks, it will shares its working schedule with all its neighboring nodes dynamically which are in the maximum transmission range of the sensor node. The maximum transmission range is adjustable and depends on the battery storage of sensor node.

IV. Method and Design

In this section, we introduce how to reduce E2E delay by the method of augmenting active instance of node. In the network, a sensor node should deliver packets to adjacent node in order to minimize energy consumption. However, the node must wait for the adjacent node waking up before it delivers a packet. In this section, we discuss how to minimize E2E delay between a sensor node and the sink by augmenting active instances of nodes if they have enough energy to support the action.

A. Description the Active Instance Augmented Scheme

If the strategy of augmenting active instance can reduce sleep latency or not depends on the order of active instance of nodes in the network. To illustrate this concept further, Fig. 3 shows three examples including three sensor nodes in a liner network. The working schedule for three sensor nodes a, b, and c are $T_a=\{2\}$, $T_b=\{6\}$ and $T_c=\{5\}$,respectively, as is shown in Fig.3 (a). We assume the three sensor nodes are in a nodes sequence $\{N_i, N_{i+1}, N_{i+2}\}$ which means the node with serial number N_{i+2} is more closely than N_{i+1} to the sink. There are two possibilities when the active instance value of node N_i compare to node N_{i+2} such as the active instance value of node N_i is lower than node N_{i+2} or larger than node N_{i+2} .

In our paper, we can say $T_i < T_{i+2}$ if the active instance of node N_i is lower than the active instance of node N_{i+2} , such as $T_i=\{2\}$ and $T_{i+2}=\{5\}$. We discuss the size of active instance of node how to affect the sleep latency. There are three possibilities for active instance of node N_{i+1} comparing to the active instances of node N_i and node N_{i+2} when $T_i < T_{i+2}$ including $\{T_i, T_{i+1}, T_{i+2} \mid T_i < T_{i+2} < T_{i+1},\ T_{i+1} < T_i < T_{i+2},\ T_i < T_{i+1} < T_{i+2}\}$ in the network, where T_i denotes the active instance of node N_i. We discuss the strategy how to affect the E2E delay in the three possibilities respectively. If $\{T_i, T_{i+1}, T_{i+2} \mid T_i < T_{i+2} < T_{i+1}\}$, the original E2E delay:

$$d_{i,i+2}(T_i, T_{i+2}) = T_{i+2} + \Gamma - T$$

Γ denotes the unit of a period duration time. If node N_{i+1} augments one active instance $T_{i+1}^{'}$ to its working schedule, where, $T_i < T_{i+1}^{'} < T_{i+2}$, the new E2E delay reduces to $T_{i+2} - T$. Therefore, the E2E delay is decreased significantly. For instance, the working schedules for three sensor nodes a, b, c are set to be $T_a=\{2\}$, $T_b=\{6\}$ and $T_c=\{5\}$ in a linear network, as is shown in Fig. 3 (a). The sleep latency $d_{ab}(2,6)$ from node a to node b is 4 units of time and $d_{bc}(6,5)$ from node b to node c is 9 units of time. So the original E2E delay $d_{bc}(2,5)$ from node a to node c is 13 units of time. However, if node b augments one active instance $T_b^{'}=\{3\}$, the new E2E delay $d_{ac}(2,5)$ reduces to 3 units of time. The E2E delay reduces 10 units of time which is duration of a period time by augmenting one active instance to node b . When $\{T_i, T_{i+1}, T_{i+2} \mid T_{i+1} < T_i < T_{i+2}\}$, the new E2E delay also decreases greatly, as is shown in Fig. 3 (b). If $\{T_i, T_{i+1}, T_{i+2} \mid T_i < T_{i+1} < T_{i+2}\}$, the E2E delay does not decrease while using the active instance augmentation scheme, as is shown in Fig. 3 (c).

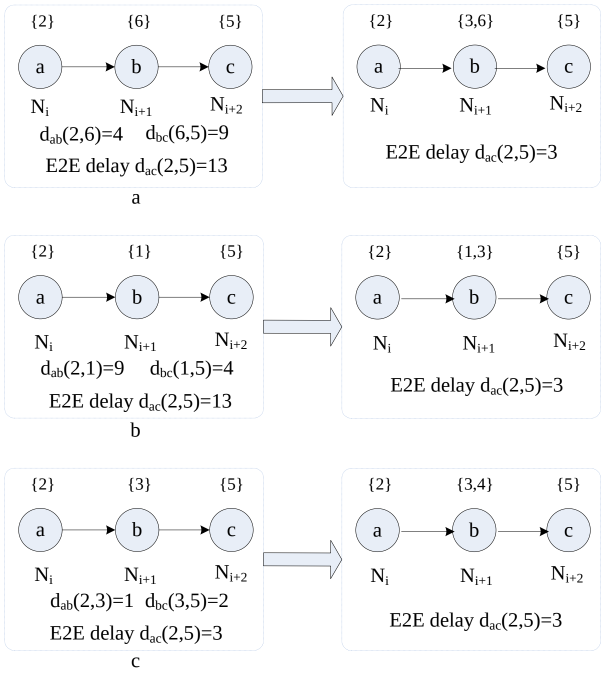

Figure. 3. Example of active instance augmentation in different scenarios when $T_i < T_{i+2}$.

Three cases of different magnitude between nodes causing sleep latency are analyzed when $T_i < T_{i+2}$ in the network. The E2E delay can be reduces only two cases when $\{T_i, T_{i+1}, T_{i+2} \mid T_i < T_{i+2} < T_{i+1}\}$ or $\{T_i, T_{i+1}, T_{i+2} \mid T_{i+1} < T_i < T_{i+2}\}$ using active instance augmented scheme. In each operation, the E2E delay can reduce a period time of duration while utilizing active instance augmented scheme. If $\{T_i, T_{i+1}, T_{i+2} \mid T_i < T_{i+1} < T_{i+2}\}$, the active instance augmented scheme can not decrease the E2E delay. When $T_i > T_{i+2}$, there are also three possibilities for active instance value of node N_{i+1} comparing to the active instances of node N_i and node N_{i+2} in the network, such as, $\{T_i, T_{i+1}, T_{i+2} \mid T_{i+1} > T_i > T_{i+2}\}$, $\{T_i, T_{i+1}, T_{i+2} \mid T_i > T_{i+2} > T_{i+1}\}$ and $\{T_i, T_{i+1}, T_{i+2} \mid T_i > T_{i+1} > T_{i+2}\}$. In the following section, we discuss whether the active instance augmented scheme can reduce E2E delay in the three possibilities respectively.

If $\{T_i, T_{i+1}, T_{i+2} \mid T_{i+1} > T_i > T_{i+2}\}$ or $\{T_i, T_{i+1}, T_{i+2} \mid T_i > T_{i+2} > T_{i+1}\}$, the E2E delay does not decrease while using the active instance augmented scheme, as are shown in Fig. 4 (a) and Fig. 4 (b). However, if $\{T_i, T_{i+1}, T_{i+2} \mid T_i > T_{i+1} > T_{i+2}\}$, the E2E delay decreases greatly, as is shown in Fig. 4 (c).

Three cases of the sleep latency problem are analyzed when $T_{i+2} < T_i$ in the network. When the active instance augmented scheme is used in the networks, the E2E delay can reduce a period time of duration when $\{T_i, T_{i+1}, T_{i+2} \mid T_i > T_{i+2} > T_{i+1}\}$ while can not change the sleep latency in other two cases including $\{T_i, T_{i+1}, T_{i+2} \mid T_{i+1} > T_i > T_{i+2}\}$ and $\{T_i, T_{i+1}, T_{i+2} \mid T_i > T_{i+2} > T_{i+1}\}$. From the analysis of the six scenarios, we know the E2E delay can be reduced in three cases by augmenting active instances of nodes contains $\{T_i, T_{i+1}, T_{i+2} \mid T_i < T_{i+2} < T_{i+1}$, $T_{i+1} < T_i < T_{i+2}$, $T_{i+2} < T_{i+1} < T_i\}$. We can call this is $\phi(N_i, N_{i+1}, N_{i+2})$. However, the E2E delay does not decrease in other three cases while using active instance augmented schemes. We can call this is $\varphi(N_i, N_{i+1}, N_{i+2}) = \{T_i, T_{i+1}, T_{i+2} \mid T_i < T_{i+1} < T_{i+2}$, $T_{i+2} < T_i < T_{i+1}$, $T_{i+1} < T_{i+2} < T_i\}$. Therefore, if we want to reduce the E2E delay, the relationship of every three adjacent nodes which are in an ordinal sequence $\{N_i, N_{i+1}, N_{i+2}\}$ has to satisfy the $\phi(N_i,\ N_{i+1},\ N_{i+2})$.

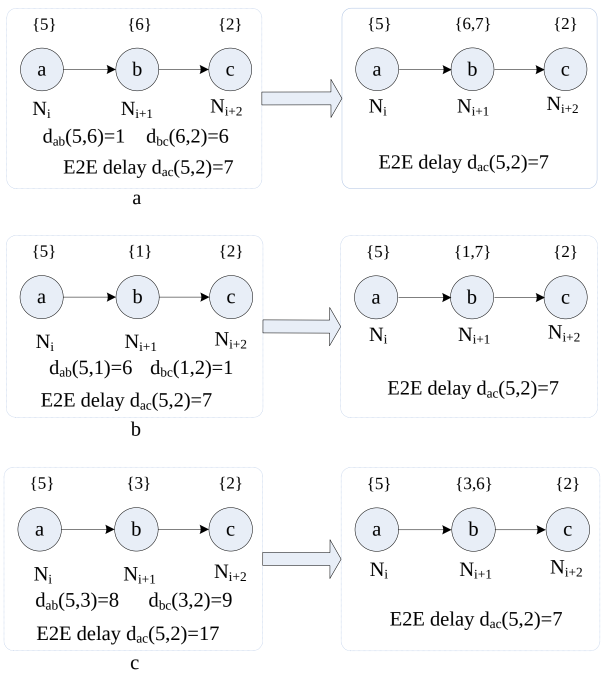

Figure. 4. Example of active instance augmentation in different scenarios when $T_{i+2} < T_i$

B. Finding the Number of Augmented Active Instances

In previous sections, we describe how to reduce E2E delay by augmenting active instances of nodes, which let nodes avoid long time waiting before delivering packets. In this section, we will discuss how to utilize this mechanism to maintain the E2E delay bound. In a network with n nodes, the longest simple path from a sensor to the sink consists of at most $n-1$ edges. Assume $d^h{}_{is}(x,s)$ denotes the E2E delay can be achieved from a node *i* to the sink *s* by augmenting at most *h* active instances, where $h \le n$.

E2E Delay: For a packet ready at source node *i*, the delay to reach the sink node *s* is the sum of single-hop sleep latency. Consequently, it can be formulated as:

$$d_{is}^0(x,s) = \sum_{i=1}^{i=n-1} d_{i,i+1}(N_i, N_{i+1}) \tag{1}$$

The number of augmented active instances: For a packet at source node *i*, the E2E delay bound *B* is the expected transmission delay to reach the sink node *s*. Assume Γ denote the units of time of duration. The least number of augmented active instances can be formulated as:

$$h = \frac{d^0{}_{is}(x,s) - B}{\Gamma} + 1 \tag{2}$$

In order to meet the E2E delay bound requirement, at least *h* active instances should be augmented to the sensor nodes in the networks. Assume there are at least *p* ordinal sequences $\{N_i, N_{i+1}, N_{i+2}\}$ can satisfy the $\phi(N_i,\ N_{i+1},\ N_{i+2})$ in the networks, where $p \le n-2$. When $h \le p$, after augmenting *h* active instances, the new E2E delay can be express as:

$$d^h{}_{is}(x,s) = \sum_{i=1}^{i=n-1} d_{i,i+1}(N_i, N_{i+1}) - \Gamma h \tag{3}$$

If a ordinal nodes sequence $\{N_i,\ N_{i+1},\ N_{i+2}\}$ can not satisfy the $\phi(N_i,\ N_{i+1},\ N_{i+2})$, after augmenting an active instance, the E2E delay reduction is lower than a period time of duration. Therefore, the corresponding E2E delay can be written as:

$$\begin{aligned} \sum_{i=1}^{i=n-1} d_{i,i+1}(N_i, N_{i+1}) - \Gamma h \le d^h{}_{is}(x,s) \\ \le \sum_{i=1}^{i=n-1} d_{i,i+1}(N_i, N_{i+1}) \end{aligned} \tag{4}$$

C. Maintaining E2E Delay Bound

In this part, we only consider when h is lower than p and a sensor node can deliver packets to its one-hop away node. From the preceding analysis, the E2E delay can be reduced a duration of units by utilizing the active instance augmented scheme every time if and only if adjacent three nodes $\{N_i, N_{i+1}, N_{i+2}\}$ can satisfy $\phi(N_i, N_{i+1}, N_{i+2})$. In our work, we not only bound the E2E delay from a node to the sink, but also make the node to communicate with its adjacent node with short distance. The E2E delay maintenance procedure goes as follows:

1) Firstly, node N_i checks whether its original E2E delay falls below the bound *B*. Specifically, $d^0{}_{is}(x,s)$ states the minimal delay from the node N_i to the sink s without any active instances augmentation. If $d^0{}_{is}(x,s) \le B$, there is no any action initiate at node N_i. Otherwise, node N_i initiates active instance augmentation process below.

2) If $d^0{}_{is}(x,s) > B$, calculates the smallest value of h by applying equation 2. In this way, we guarantee minimal energy consumption for bounding E2E delay from source node N_i to the sink s.
3) According to the value of h, if $h > 0$ and $i+2 < n$, the active instances augmentation mechanism will be adopted from node N_i to its one-hop and two-hop away nodes if and only if them meet $\phi(N_i, N_{i+1}, N_{i+2})$ = $\{T_i, T_{i+1}, T_{i+2} \mid$ $T_i < T_{i+2} < T_{i+1}$, $T_{i+1} <$ $T_i < T_{i+2}$, $T_{i+1} <$ $T_{i+2} < T_i\}$. Then, one new active instance T'_{i+1} is augmented to the working schedule of node N_{i+1}. Now, there are two active instances $\{T_{i+1}, T'_{i+1}\}$ in node N_{i+1}. Among them, the new active instance T'_{i+1} meets the requirement $T_i < T'_{i+1} < T_{i+2}$. At the same time, $h = h-1$, $i = i+1$, return 3).
4) If $h > 0$ and $i+2 < n$, the ordinal sequences $\{N_i, N_{i+1}, N_{i+2}\}$ belongs to $\varphi(N_i, N_{i+1}, N_{i+2}) = \{T_i,$ T_{i+1}, $T_{i+2} \mid T_i <$ $T_{i+1} <$ T_{i+2}, $T_{i+2} < T_i < T_{i+1}$, $T_{i+1} <$ T_{i+2} $< T_i\}$, $i =$ $i+1$, return 3).
5) When $h = 0$ or $i+2 = n$, Now, calculate the value of $d^h{}_{is}(x,s)$ by applying equation 1, if $d^h{}_{is}(x,s) \le B$, the process is terminated.

The procedure of bound the E2E delay is in according with FIFO property. Therefore, all sensor nodes are in a sequence $\{N_1, N_2, \ldots, N_n\}$ according to the distance from source node to the sink along the path. When E2E delay is above the E2E delay bound in the network, the first node initiates active instance augmentation process. The order of augmenting active instances of nodes are from the first node which is called source node and farthest to the sink to the adjacent node which is second farthest to the sink until the node is one-hop away the sink or the number of active instances augmentation h is 0.

In the process of implementation, it is sufficient for a node to know whether the value of active instances augmentation h is 0 from its previous node. If h is bigger than 0, by comparing its active instance to its previous node and following node, the node decides whether or not to augment an active instance to its working schedule. Since the time complexity of delay maintenance at individual nodes is just $o(1)$, the total time complexity is $o(n)$ for bounding E2E delay from a node to the sink.

V. Simulations

In the simulation, up to 300 nodes are randomly deployed in a 500m×500m square field. The maximum communication range is set to be 50m. All nodes' transmission power is adjustable. Every two nodes can communicate directly with each other in the transmission range. Except some cases, the default number of nodes in the network, node duty cycle and delay bound is 300, 2% and 250 units of time, respectively. Every data point in simulation Figures is obtained by averaging 50 runs with different random seeds, node deployment and node working schedules.

In a rechargeable wireless sensor networks, energy harvesting rate varies significantly over time and is affected by the environment conditions. Fig. 5 shows sample node relying on the sun energy harvesting rates over 24 hours. In Fig. 5, we know a node will extract more energy on sunny days and extract no energy at night at all. The energy supply significantly affects a node's duty cycle. Fig.6 shows a node duty cycle over 24 hours. The duty cycle of node is very low and is almost near 0 from time 0 to 5. The node increases its duty cycle gradually from time 5 and achieve peak around time 13. The node decreases its duty cycle from time 14 to 20 and is in a dormant sate again from time 20 to 24. In Fig. 6, within time interval [12], [14], the duty cycle of node can achieve 30%. In contrast, during time [20]-[24] and [0-5], the duty cycle of node is around 0 and node has to keep in dormant state in the period time.

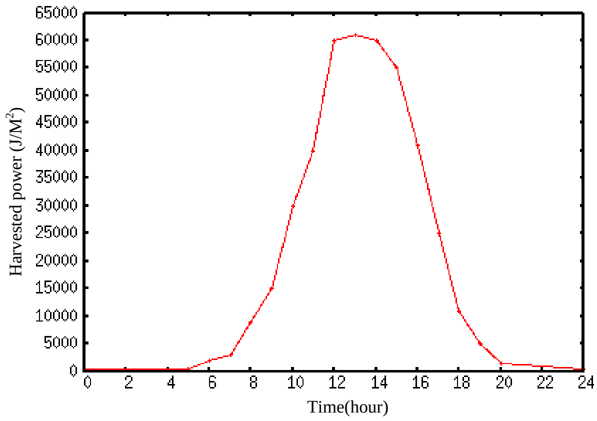

Figure. 5. Sample node energy harvesting rate.

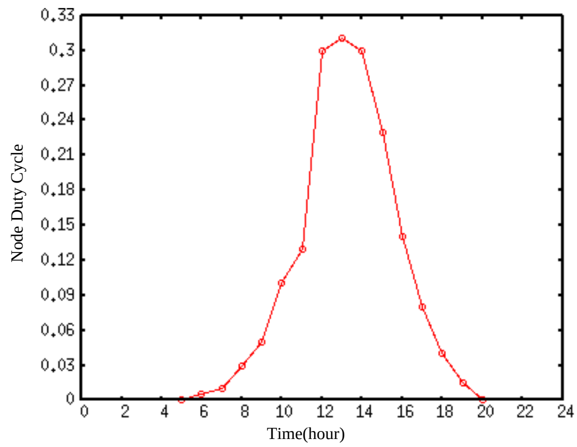

Figure. 6. Node duty cycle over time.

In order to understand the performance of our delay maintenance design under network settings, in this section, we provide an algorithm (Duty cycle based Adaptive toPOLogical KR aLgOrithm, D-APOLLO) for performance comparison, which is proposed by Noh *et al* [8]. In [8], the author provides a duty cycle based low latency geographic routing for asynchronous energy harvesting WSNs. We introduce an improved version of the algorithm, which only the duty cycle of every node is determined periodically and locally. Duty cycle of each node can be changed dynamically in order to meet E2E delay requirement. We will compare the number of augmented active instances for delay maintenance and the D-APOLLO to achieve delay bound through several experiments.

Fig. 7 shows the number of augmented active instances under various delay bounds. With delay bound increased, the number of augmented active instances decreases gradually for both schemes. This is because with looser delay bound from all nodes to the sink in the network, there are few nodes being in routing paths whose E2E delays are still beyond the bound. Therefore, smaller number of active instances is augmented to the network. In Fig. 7, we know the number of active instances of delay maintenance augments is less than that of D-APOLLO at all delay bounds. In average, the number of active instances of delay maintenance augments is about 20% less than that of the D-APOLLO.

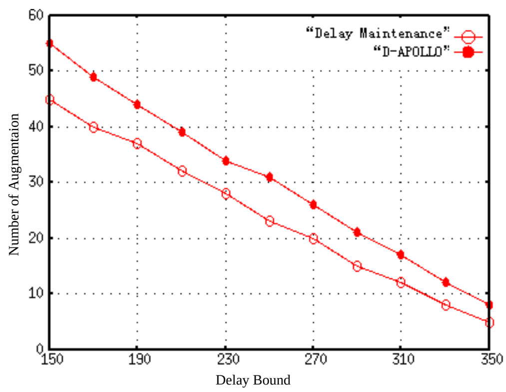

Figure. 7. Comparative E2E delay for different active instance augmentation.

In addition to large scale simulations, we implement our design with 20 nodes to further validate our scheme in practice. We deploy 20 nodes and a sink node along a straight line. The transmission power at node is tuned down so that a node only communicates with adjacent node directly. All nodes and the sink node form a 20-hop linear network. Source node is 20-hop away from the sink node. Hence, other common nodes will forward the packets from source node to the sink node. After deployment, every node initiates to generate working schedule randomly with 10% duty cycle, which means every node can generate only an active instance within each period time.

Every node owns an active instance. Then, every node in the linear network initiates to broadcast its existence and working schedule to its adjacent neighbors. Followed by neighbor discovery, every node only knows the working schedules of adjacent neighbors and does not need to know others'. Every node calculates the sleep latency between itself and its neighbor node. Then, the node calculates the delay from source node to its neighbor node and sends the result to its neighbor node. Finally, the sink node can receive the E2E delay result and initiates delay computation process and nodes in the network start to execute delay maintenance process.

Fig.8 shows the E2E delay in the network with different active instance augmentation by both schemes. The E2E delay drops dramatically for both designs. Clearly, in all different active instance augmentation, our delay maintenance design has smaller E2E delay than D-APOLLO scheme. On the other hand, the E2E delay of delay maintenance scheme drops more quickly than that of D-APOLLO with active instance augmentation increasing. To further reveal the insights of different performance between delay maintenance and D-APOLLO, in Fig. 9 we provide E2E delay reduction result from all nodes to the sink under varying number of augmented active instance. From Fig. 9, we can see the delay maintenance has much larger E2E delay reduction than that of D-APOLLO at all augmented active instance. For instance, after augmenting 5 active instances, delay maintenance scheme reduces E2E delay by 50 while D-APOLLO only reduces 38, therefore, the reduction of E2E delay is about 30% higher than that of D-APOLLO.

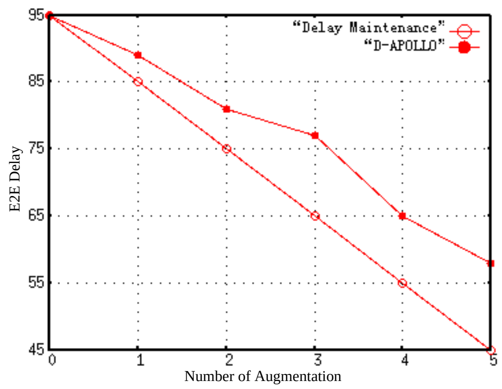

Figure.8. Comparative E2E delay for different active instance augmentation.

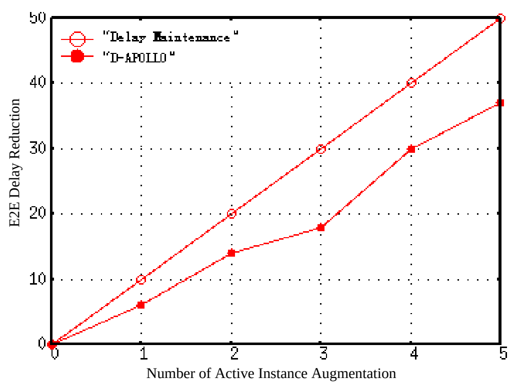

Figure.9. Comparative E2E delay Reduction for different active instance augmentation.

To investigate the impact of delay bound, Fig. 10 shows the number of augmented active instances under various delay bounds, which is 20-hop away from the source node to the sink. From Fig. 10, we can see the number of augmented active instances decreases dramatically for both schemes with delay bound increasing. This is because with looser delay bound from all nodes to the sink in the network, there are fewer nodes whose E2E delays are still beyond the bound. Therefore, smaller number of active instances is augmented to the network. In Fig. 10, we know delay maintenance augments less number of active instances than that of D-APOLLO in all delay bounds. When delay bound is set to be 45, the number of active instances of delay maintenance augments about 20% less than that of the D-APOLLO.

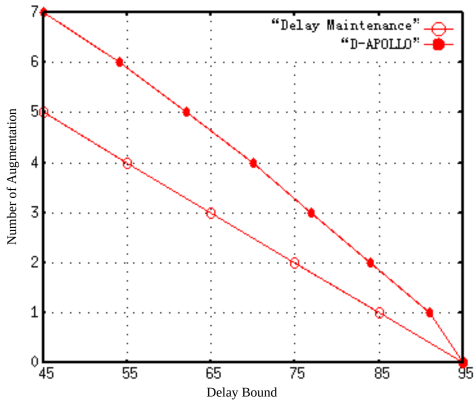

Figure.10. Comparative number of augmentation for different delay bound.

VI. Conclusions

In R-WSNs, due to environmental factors that lead to sporadic availability of energy, a node must adjust its duty cycle continuously, which leads to high packet delivery latency. In many WSNs applications, an E2E delay bound is required. In this work, we address the delay bound problem. Specifically, we seek to reduce the E2E delay using the least amount of energy expenditure. In a nutshell, we propose a distributed active instance augmentation algorithm to bound the E2E delay for sources to sink communications in R-WSNs.

We first define the network model and elaborate on the packet delivery process. We introduce the active instance augmented scheme and provide an algorithm for finding the minimal delay from a node to the sink by augmenting minimal h active instances. In addition, we introduce how node can reduce two-hop delay by comparing its active instance to its predecessor and successor nodes in the network. For bounding E2E delay from source node to the sink in the network, we propose an E2E delay maintenance solution. Through extensive simulation and experiments, we demonstrate our delay bound maintenance scheme is efficient to provide E2E delay guarantees in rechargeable wireless sensor networks.

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