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Duty-Cycle-Aware Minimum Energy Multicasting of Passive RFID Wake-up Radios for Wireless Sensor Networks

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Abstract-
In duty-cycled wireless sensor networks, the nodes switch between active and dormant states, and each node determine its active/dormant schedule independently. This complicates the Minimum Energy Multicasting (MEM) problem in wireless sensor networks both for one-to-many multicasting and for all-to-all multicasting. In the case of one-to-many multicasting, we present a formalization of the Minimum-Energy Multicasting Tree Construction and Scheduling (MEMTCS) problem. We prove that MEMTCS problem is NP-hard and propose a polynomial-time approximation algorithm for the MEMTCS problem. In the case of all-to-all multicasting, we prove that the Minimum-Energy Multicast Backbone Construction and Scheduling (MEMBCS) problem is also NP-hard and present an approximation algorithm for it. Compared to duty cycling, wake-up radios save more energy by reducing unnecessary wake-ups and collisions. In this paper, we investigate the feasibility and potential benefits of using passive RFID as a wake-up radio. We first introduce a physical implementation of sensor nodes with passive RFID wake-up radios and measure their energy cost and wake-up probability. Then, we compare the performance of our RFID wake-up sensor nodes with duty cycling in a Data MULE scenario through simulations with realistic application parameters. Finally, we perform extensive simulations, and the results show that using a passive RFID wake-up radio offers significant energy efficiency benefits at the expense of delay and the additional low-cost RFID hardware, making RFID wake-up radios beneficial for many delay-tolerant sensor network applications.
Index Terms- Approximation algorithm, duty-cycle-aware,
Minimum-energy, multicasting, wireless sensor networks (WSNs), wake-up receiver, passive RFID wake-up, data MULE.

I. INTRODUCTION

Wireless sensor networks (WSNs) are decentralized systems without any pre-existing infrastructures, and the sensor nodes are usually powered by batteries. As the limited battery lifetime imposes a severe constraint on the network performance, it is imperative to develop energy conservation mechanisms for WSNs. One common approach for energy conservation in WSNs is duty-cycling, in which each node switches between active and dormant states, and the active/dormant schedule can vary from node to node [1]–[5]. Duty-cycling is easily implementable and is proven to be an effective way for energy conservation [1]. As a result, duty-cycled wireless sensor networks (DC-WSNs) have been adopted by various applications [6]–[8].

As a crucial component of wireless networking, multicasting has been applied to WSNs in supporting data dissemination for distributed data management (e.g., [9]). Therefore, designing an energy-efficient multicast protocol is of great importance. In an always-active wireless ad hoc network (AA-WANET), the network topology is static, and each forwarding node can cover all its neighbouring nodes by only one transmission. Therefore, the main task of the Minimum-Energy Multicasting (MEM) problem in AA-WANETs is to select appropriate forwarding nodes such that a multicast tree with minimum energy cost can be constructed. This problem was proved to be NP-hard, and some approximation algorithms have been proposed [10]–[13].

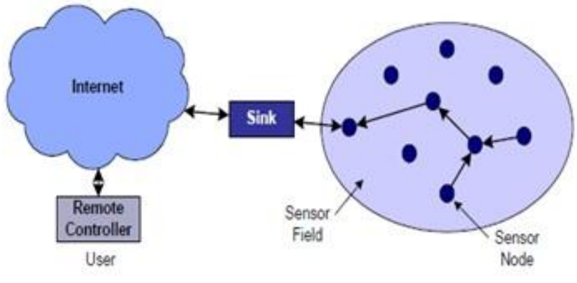

FIG.1. Sensor network architecture

In DC-WSNs, however, new challenges to the MEM problem arise. More specifically, the network topology is now only intermittently connected, and a forwarding node may need to transmit the same data packet many times to reach its neighbouring nodes. Therefore, designing energy-efficient multicasting algorithms in DC-WSNs requires not only that the forwarding nodes should be selected appropriately to construct a multicast tree, but also that the transmissions of each forwarding node need to be scheduled intelligently to cover the receiving nodes with a minimum number of transmissions. More importantly, these two aspects must be handled jointly so that the total energy cost can be reduced to the largest extent. Consequently, the existing solutions for the MEM problem in AA-WANETs are not suitable for DC-WSNs, and we need to design new energy-efficient multicasting algorithms to meet the challenges in DC-WSNs.

Idle listening, when a sensor node is active and waiting to receive data, is a large source of energy drain in WSNs. Generally there are two approaches to reduce the energy consumption due to idle listening: duty cycling the node and using a wake-up radio. Since sensor nodes do not have data to send all the time, it is common to use duty cycling, where the nodes are periodically set into the sleep mode. Duty cycling saves a significant amount of energy at the expense of latency in data delivery. However, one problem in utilizing duty cycling is that the nodes wake up periodically regardless of whether or not any other nodes have data to transmit to them. In this situation, the nodes waste significant energy due to unnecessary wake-ups.

Wake-up radios can be classified into two categories as active and passive wake-up radios. Active wake-up radios consume power, but they have better wake-up ranges than passive wake-up radios. Passive wake-up radios use the energy harvested from the wake-up radio and thus operate over short ranges. One possibility is to use passive RFID as the wake-up technology, as there are off-the-shelf passive RFID tags and readers readily available. A major drawback of using passive RFID tags for the wake-up functionality is that multi-hop communications cannot be supported due to the large size and large power consumption of the RFID reader. It is not yet practical to equip all sensor nodes with RFID readers. Additionally, it is not known how well passive RFID would perform as a wake-up radio, in terms of wake-up distance, wake-up probability, and energy consumption for the sensor node to be woken up. Hence, determining the feasibility of using passive RFID for a wake-up radio and the potential benefits of such a wake-up radio in real scenarios require a separate study, which is the aim of this paper.

In this paper, we describe a physical implementation of a passive RFID wake-up device using existing hardware. By combing WISP (Wireless Identification and Sensing Platform) passive RFID tags developed by Intel Research [13] with Tmote Sky motes [14], we created a passive RFID wake-up device, which is referred to as a *WISP-Mote* in this paper. We characterize the performance of the WISP-Motes by measuring the power consumption in different operation stages, including sleeping, wake-up, transmitting and receiving, and by testing the wake-up probability for different ranges. To show the benefits of WISP-Motes, and hence the benefits of passive RFID-based wake-up radios, we compare the use of WISP Motes with a standard mote architecture that utilizes duty cycling for a single-hop Data MULE [15] data collection scenario.

A. *Background and Motivations*

The MEM problem in AA-WANETs has the minimum-power multicast routing problem in a scenario where each node can adjust its transmission power continuously, and the communication links can be symmetric or asymmetric. Each wireless node can adjust its transmission power in a discrete fashion and the communication links are symmetric. We study the minimum-energy all-to-all multicasting problem in such a network and tried to build a shared multicast tree such that the total energy consumption of realizing an all-to-all multicast session by the tree is minimized and proved that finding such a multicast tree is an NP-complete problem and proposed several approximation algorithms for it. All the aforementioned algorithms assume that the network nodes are always-active; they cannot directly apply to DC-WSNs.

B. Our Contributions

In this paper, we study the MEM problem in DC-WSNs using a generic duty-cycling model, where each wireless node determines its active/dormant schedule without any constraints. We formulate the MEM problem for DC-WSNs in the case of both one-to-many multicasting and all-to-all multicasting. We prove the NP-hardness of these two problem instances, and we propose approximation algorithms with guaranteed performance ratios. We also present a distributed implementation of our algorithms. Moreover, we propose a simple but efficient collision- free scheduling scheme on top of a multicast tree to avoid packet loss. Our main contributions are summarized as follows.

1) In one-to-many multicasting, we formulate the Minimum-Energy Multicast Tree Construction and Scheduling (MEMTCS) problem and prove its NP-hardness. We also prove that, unless $NP \subseteq DTIME(n^{O(\log\log n)})$, the MEMTCS problem cannot be approximated within a performance ratio of $(1-o(1))\ln\Delta$, where Δ is the maximum node degree of the input network.
2) We propose a polynomial-time approximation algorithm for the MEMTCS problem with an approximation ratio of $6\rho H(\Delta+1)+2\rho$, where $H()$ is the harmonic number and ρ is the approximation ratio of a given algorithm for the Minimum Steiner Tree (MST) problem.
3) In all-to-all multicasting, we formulate the Minimum-Energy Multicast Backbone Construction and Scheduling (MEMBCS) problem and prove its NP-hardness. We present an approximation algorithm for the MEMBCS problem, which has the same performance ratio as the proposed algorithm for the MEMTCS problem.
4) We present a distributed implementation of the proposed algorithms, and we conduct extensive simulations to evaluate the performance of our algorithms. The simulation results demonstrate that our algorithms significantly outperform other known algorithms in terms of the total transmission energy cost.

We propose a collision-free scheduling scheme on top of a multicast tree (constructed by our algorithm for either MEMTCS or MEMBCS) in DC-WSNs. The simulation results based on this scheme show that the delay performance of our multicast trees is comparable to other proposals in the literature.

To the best of our knowledge, we are the first to present polynomial-time approximation algorithms with provable approximation ratios for the MEM problem in DC-WSNs. Moreover, as the Minimum-Transmission Broadcasting/Gossiping problems can be seen as special cases of our problem, we also provide the first approximation algorithms with provable approximation ratios for these problems in DC-WSNs under a generic duty-cy-cling model.

C. Network Model and Parameters

A WSN is modelled by an undirected graph G = (V, E), where V is the set of wireless nodes, and E is the set of links.

TABLE I
SYMBOLS AND NOTATIONS

Notation	Description
G	The graph representing a WSN
V	Node set of G
E	Edge set of G
K	Length of the working period of any node in V
M	The terminal set
S	The source node in one-to-many multicasting
e_s	The energy cost for sending a data packet
$\overline{\Gamma(u)}$	Set of active time slots in the working period of u
$nb_G(u)$	Set of neigh-boring nodes of u in G
nl (T)	Set of non-leaf nodes in rooted tree T
N (T)	Set of nodes in tree T
E (T)	Set of edges in tree T
Child(u, T)	Set of child nodes of u in rooted tree T
ρ	Approximation ratio of a given algorithm for minimum Steiner tree
H(K)	The K-th Harmonic number
T_{opt}	An optimal multicast tree for a MEMTCS problem
B_{opt}	An optimal feasibility schedule for T_{opt}
Π (T, B)	The total energy cost of an one-to-many multicast tree T and the feasible schedule B
□	The extended graph of G
□	Node set of □
E□	Edge set of □
$\lambda(u,i)$	The satellite node of u on time slot i
Ψ (u)	Set of all satellite nodes of u
Vs	Set of all satellite nodes in □

□s	The sub graph of □ induced by Vs
$\Upsilon(u,T)$	A minimum hitting set of collection { $\Gamma(v)$ | $v \in nb_T(u)$}
SB*	A minimum satellite bridge
Δ	The maximum node degree in G
$d^1(T)$	Set of nodes in T with degree one
$d^+(T)$	Set of nodes in T with degree greater than one
$\Xi(T)$	Summation of $\vert\Upsilon(u,T)\vert$ over all those u $\in d^+$ (T)
T_I	A minimum isotropic scattering tree

The nodes in V are distributed in a two-dimensional plane, and each node is equipped with a unidirectional antenna. All nodes have the same fixed transmission power, and there exists a link between two nodes if they are within the transmission range of each other. We also assume that each node has a unique ID and knows the IDs of its one-hop neighbours.

We assume that time is divided into equal-length slots, and each *time-slot* is long enough for sending or receiving a data packet. Without loss of generality, we assume that the working schedule of each node is periodic, and the *working period* of any node has K time-slots. We assume that *a node can wake up its transceiver to transmit a packet at any time-slot, but can only receive a packet when it is active*. We also assume that time synchronization is achieved in network, and each node knows the active/dormant schedule of its neigh boring nodes. These are common assumptions in the literature [2]–[5].Finally, we assume that a packet transmission is always successful unless it collides with other transmission(s).[1]

II. MEMTCS PROBLEM

We first briefly evaluate the hardness of MEMTCS. We prove it is NP-hard using a reduction from the Minimum Hit-ting Set (MHS) problem [11], and we claim this in Theorem 1.

Theorem 1: The MEMTCS problem is NP-hard.

The MHS problem was proved to be equivalent to the Minimum Set Cover (MSC) problem [12]. Moreover, NP has quasi-polynomial-time algorithms, there exists no polynomial - time algorithm for the MSC problem with performance ratio of $(1-o(1))\ln n$, where n is the size of the MSC problem. Therefore, with the proof of Theorem 1, we can easily get the following corollary.

Corollary 1: Unless $NP \subseteq DTIME(n^{O(\log\log n)})$, there exists no polynomial-time approximation algorithm with performance ratio of $(1-o(1))\ln\Delta$ for the MEMTCS problem, where Δ is the maximum node degree of a WSN. Next, we propose an approximation algorithm for the MEMTCS problem [10]. We first provide a brief overview of our algorithm in Section II-A, then describe our methods in details from Sections II-B–II-E.

A. Overview of the Proposed Algorithm

Our approximation algorithm consists of several steps. First, we use a graph transformation method to extend the original net-work graph G into G, where the possible transmitting time-slots of the nodes in G are represented as *satellite nodes*, and the nodes in G are connected in a particular way to facilitate the design of our approximation algorithm (Section II-B). Second, we propose the concept of *Minimum Satellite Bridge* (MSB) in G as well as an algorithm for finding an approximation MSB. The MSB is actually a special tree in $\tilde{G}$ whose nodes can cover all the nodes in M (Section II-C). Finally, we map the approximation for MSB to a multicast tree in G and a feasible schedule for the multicast tree (Section II- E).

This resulting multicast tree along with its schedule serves as an approximate solution to the MEMTCS problem. To find the approximation ratio of our algorithm, we propose another concept, *Minimum Isotropic Scattering Tree* (MIST); it is a special multicast tree T_I in G spanning the nodes in M (Section III-D). We prove that T_I serves as a quantitative "bridge" between the number of nodes in an MSB and

$\langle T_{\bullet t} B_{ot} \rangle$. As a result, we obtain the approximation ratio of our algorithm.

B. Graph Transformation

The first step of our approach is to transform the original net-work graph into an extended graph. Note that the work in [5] has also provided a graph transformation method, and one can use it to convert the MEM problem into an instance of the DST problem. Unfortunately, the best-known approximation ratio of any polynomial-time algorithm for the DST problem is only linear [9]. In contrast, employing our new graph transformation method proposed enables us to apply an MST algorithm and hence leads to a much better logarithmic approximation ratio for the MEM problem.

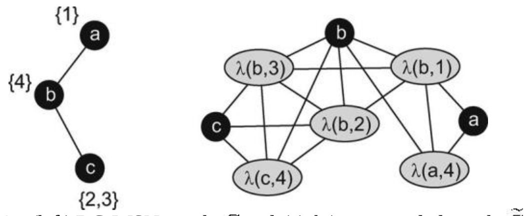

Fig. 2. *(left)* DC-WSN graph G and *(right)* its extended graph $\widetilde{G}$.

Any two nuclear nodes cannot be adjacent in $\widetilde{G}$, and any satellite node in V_S can be adjacent to at most $\Delta+1$ nuclear nodes in G.

C. Minimum Satellite Bridge

We first introduce the concept of MSB in Definition 6, and then we propose an approximate algorithm for finding an MSB. Though an MSB does not directly lead to a solution, it is an important building block of our algorithm for solving the MEMTCS problem.

Definition 1 (Minimum Satellite Bridge):

Given $\widetilde{G}=(\widetilde{V},\widetilde{E})$ and the terminal set $M \subseteq V$, a *Satellite Bridge* SB is a sub tree of $\widetilde{G}$ that satisfies the following.

1) The nodes in SB are all satellite nodes.
2) Each node in the terminal set M is adjacent to at least one node in SB.

Next, we propose an approximation algorithm with a performance ratio of $\mathcal{O}(H(\Delta+1))$ for finding an MSB. The idea of our algorithm is to first find a small set of satellite nodes covering all the nodes in M, and then connect these satellite nodes to get a satellite bridge. This is shown in Algorithm 1.

Algorithm 1: Finding an approximate **MSB**

Input: The extended graph $\widetilde{G}$ and the terminal set M

Output: An approximate MSB $\overline{SB}$

1 C ← ø, UC ← M

2 While UC ≠ ø **do**

3 v ← arg $\max_{u \in V_S - C} |nb_{\widetilde{G}}(u) \cap UC|$

4 C ← C U {v}; UC ← UC - $(nb_{\widetilde{G}}(v) \cap UC)$

5 Let $\widetilde{G}_s$ be the sub-graph of $\widetilde{G}$ induced by V_s. Assign each edge in $\widetilde{G}_s$ a weight of 1. Compute an approximate minimum Steiner tree ST in $\widetilde{G}_s$ which connects the nodes in C; $\overline{SB}$ ← ST

We can see that Algorithm 1 consists of two stages. The first stage is lines 1–4, and the second stage is line 5. In the first stage, we use a greedy set cover algorithm to find a small node set C that can cover all the nodes in M. In each loop, we first find a node v that has the maximum number of adjacent nodes in the uncovered node set UC (line 3). Then, we add v into C and update UC (line 4). In the second stage, an approximate Steiner tree algorithm is applied upon C.

D. Minimum Isotropic Scattering Tree

Now we link an MSB to a special tree in G called the MIST and a feasible schedule for the internal nodes in MIST. Although an approximate MSB will be involved to construct an approximation to MEMTCS in Section II-E, the quantitative relation between an MSB and an optimal solution to MEMTCS is not straightforward. Therefore, we use MIST as a medium to de-rive the approximation ratio.

This mapping procedure and its outcome can be roughly described as follows. According to the construction rules of the extended graph, the satellite nodes in a satellite bridge can be mapped to the nuclear nodes that they belong to, as well as the transmitting time-slots on these nuclear nodes. Furthermore, we can find a tree spanning these mapped nuclear nodes and the terminal nodes in M, and most importantly, the internal nodes in this tree are all the mapped nuclear nodes. According to the special node-connecting method of the extended graph, the mapped transmitting time-slots of any internal node in this tree can cover its entire neigh boring nodes in the tree.

E. Approximation Algorithm for MEMTCS

Based on the methods introduced by the previous sections, we propose our algorithm for the MEMTCS problem, as shown in Algorithm 2.

Algorithm 2: Approximation for **MEMTCS**

Input: A DC-WSN G, a terminal set M, and a source node s ∈ M

Output: A multicast tree $\bar{T}$ and a feasible schedule $\bar{B}$

1 Construct the extended graph $\bar{G} = (\bar{V}, \bar{E})$ of G

2 Use **Algorithm 1** to compute an approximate minimum satellite bridge $\overline{SB}$

3 Use the method to map $\overline{SB}$ to a 2-tuple <$\bar{T}$, $\bar{F}$>. Let $\bar{T}$ be the rooted tree resulting from designating s as the root of $\hat{T}$

4 **for each** node u ∈ nl ($\bar{T}$) **do**

5 **if** u ∈ d^+ ($\bar{T}$) **then**

6 Prune the time slots in $\hat{F}$ (u) that do not cover any Child nodes of u in $\bar{T}$; $\bar{B}$ (u) ← $\hat{F}$ (u)

7 **else**

8 Let v be u's child node in $\bar{T}$. Find an arbitrary i ∈ Γ (v); $\bar{B}$ (u) ← {i}

The **output** of Algorithm 2 is a 2-tuple $\bar{T}\,\bar{B}$.

III. MEMBCS PROBLEM

Just as the MEMTCS problem, the MEMBCS problem is also NP-hard. We claim this in Theorem 5. The NP-hardness of the MEMBCS problem can be proved by using a reduction from the Maximum Leaf Spanning Tree (MLST) problem [12].

Theorem 2: The MEMBCS problem is NP-hard.

Next, we provide an approximation algorithm for the MEMBCS problem, as shown in Algorithm 3. We can see that Algorithm 3 is actually adapted from Algorithm 2 and has the same time complexity as Algorithm 2. Note that the transmission schedule of any internal node in P is actually obtained by using the mapping method.

Algorithm 3: Approximation for the **MEMBCS** problem

Input: A DC-WSN G and a terminal set M.
Output: A multicast backbone P and a set of feasible schedules for the rooted trees in $\{P^{(m)} | m \in M\}$.

1. Find an arbitrary node v in M.
2. Call **Algorithm 2** to get a multicast tree $\bar{T}$ rooted at v and a feasible schedule $\bar{B}$ for $\bar{T}$.
3. Let P be the un-rooted tree that has the same edges and nodes as $\bar{T}$.
4. For any node m ∈ M and any node u ∈ $d^{+}(P)$, let $S^{(m)}(u) = \bar{B}$ (u).
5. For any node w ∈ M ∩ $d^{1}(P)$, find an arbitrary active time-slot i of the neighboring node of w in P, and let $S^{(m)}(w) = \{i\}$.

IV. THE WISP-MOTE PLATFORM

The lifetime of a wireless sensor network node is limited by the sensor node's battery supply. To extend a node's lifetime, duty cycling can be utilized. To reduce the node's energy consumption, the duty cycle must be set to a relatively low value (e.g., 10% duty cycle, which means the node is "on" for 10% of the time). However, this will increase the average data transmission latency, as packets that arrive at a node during the sleep period must be buffered until the next active period. Although there are protocols designed to reduce large delays caused by sleeping, such as DMAC [15], these approaches require additional overhead and global routing management. When a node has no information about its environment, idle listening is inevitable with the duty cycling approach. Besides idle listening, control packet overhead and synchronization overhead are also sources of energy waste observed with duty cycle approaches. All of the above issues motivate us to utilize radio wake-up techniques in wireless sensor networks to further improve energy efficiency. This section introduces the implementation of a combined passive RFID-based wake up radio and a sensor mote, which we call a WISP-Mote, and provides measurement results of the wake-up probability and the energy consumption of the WISP-Motes.

A. Radio Wake-up Basics

Most sensor nodes use a microcontroller (MCU) to provide computation and data processing, control the radio and sensors, and manage memory and power. An internal clock, called the watchdog timer, is used to wake up the system after a timer fires. By setting this timer, a node can wake up periodically to perform its functionalities. On the other hand, nodes lose their functionalities while sleeping. The only other way to wake up a node from the sleep state is to send an external interrupt signal through the pins of the MCU. Such an external interrupt signal is generated by the radio wake-up circuitry.

B. Wake-up Probability

The energy a WISP is able to harvest decreases with increasing distance due to path loss. Thus, it is important to measure the wake-up probability as a function of distance. We performed field tests of the WISP-Motes in a large hall, which is similar to an outdoor environment. We raised both the WISP and the reader's antenna off the ground to reduce multipath fading. We enabled the interrupt of the WISP-Mote periodically, and we counted the number of times the WISP Mote can be successfully woken up as a function of distance. The test results, which determine the wake-up probability, are shown in Fig. 3.

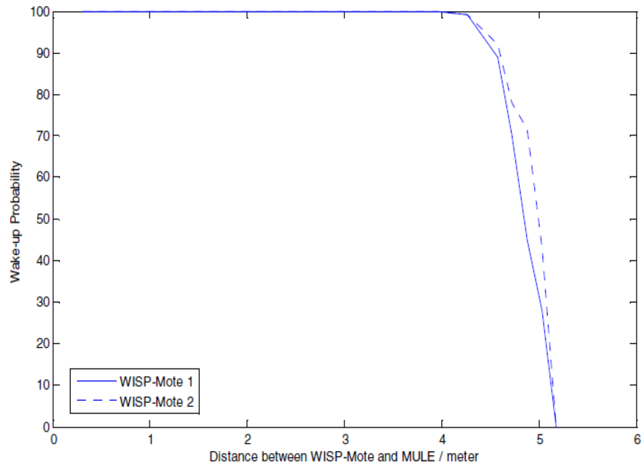

Figure 3. Wake-up probability of the WISP-Motes.

As seen in Fig. 3, the wake-up probability starts to decrease after 4 m and sharply drops down to

0 beyond 5 m. In our simulations, we use a conservative value of 4 m.

C. Energy Consumption Measurements

The major advantage of passive RFID wake-up is to reduce the energy waste of a sensor node and enhance its energy efficiency. The Tmote Sky datasheet provides the current consumptions in typical operating conditions. We measured current consumption in booting and radio initiation, which is essential for the energy consumption analysis of RFID wakeup. The results are shown in Table II. Our measurements are consistent with those from the Tmote Sky datasheet. We can see that besides radio transmission and reception, node wakeup also consumes energy that cannot be ignored. This would support the need for an accurate energy analysis for the radio wake-up mechanism when characterizing a wake-up mote.

TABLE II. POWER CONSUMPTION MEASUREMENTS OF A T-MOTE SKY NODE

Operation	**Average current consumption**	**Time**
Wake-up	10.4 mA	5 ms
Transmit 12 byte packet	18.2 mA	30 ms
Receive and idle listening	20.2 mA	
Sleep	0.2 mA	

V. USE OF WISP-MOTES IN A DATA MULE SCENARIO

The main advantage of the WISP-Motes is high energy efficiency through on-demand wake-up. However, a short wake-up range is achieved compared to the communication range. To evaluate the benefits of WISP-Motes, we consider a sparse delay-tolerant network of WISP-Motes with data MULEs that collect the sensor data. The MULE architecture provides connectivity for a sparse sensor network using single hop communications. In this scenario, one or multiple mobile
MULEs move throughout the network field collecting data from the sensor nodes. The MULEs are equipped with RFID readers and can wake up the WISP-Motes. Once a MULE is close to a sensor node (within 4 m range for our simulations), the node is awakened and senses the channel if it has buffered data. If the channel is busy, the WISP-Mote will remain active and sense again in the next slot. Once the channel is free, the WISP-Mote will start transmitting its buffered data. If the WISP-Mote is not awakened by a MULE, the node remains asleep. In real scenarios, any moving agent, such as a person, an animal, or a vehicle, could act as a data MULE.

We compare the performance of the WISP-Mote network with a network of conventional sensor nodes that utilize duty cycling to save energy. In the latter case, the MULEs periodically send advertisement packets to declare their presence. Nodes periodically wake-up, and if the node has buffered data, it will sense the channel. If a node receives an advertisement packet from a MULE, it responds by sending its buffered data. If the MULE is in communication with another node, the sensor node will keep active and sense the channel again in the next time slot. If there are no MULEs within range of the sensor node, the sensor node returns to sleep until the next duty cycle wake-up period.

VI. PERFORMANCE EVALUATION

In this section, we evaluate the performance of our algorithms via simulations. Our simulations focus on the effect of various network conditions on the performance of different one-to-many and all-to-all multicasting algorithms. In the simulations, we deploy wireless nodes randomly in a 1000 1000-m square, and the transmission range of each node is set to 300 m. Each node randomly picks some time-slots in the working period as its active time-slots. Without loss of generality, the energy cost e_s for sending a data packet by any node is set to 1.

A. Comparing to Conventional Multicasting Algorithms

To the best of our knowledge, there is no polynomial-time minimum-energy multicasting algorithms designed for DC-WSNs. Thus, we compare our algorithms with several conventional multicasting algorithms, including the *Shortest Path Tree* (SPT) algorithm, the *Approximate Minimum Steiner Tree* (AMST) algorithm, and the minimal data overhead tree (the MNT algorithm). The SPT algorithm computes shortest paths from the source node to the receiver nodes and aggregates these shortest paths to construct a multicast tree. The AMST algorithm computes an approximate minimum Steiner tree spanning all the nodes in the terminal set M. The MNT algorithm was designed for reducing the total number of transmissions for a multicast session in AA-WANETs. The work has proved that MNT can reduce the number of transmissions in a one-to-many multicast session more effectively than other heuristics.

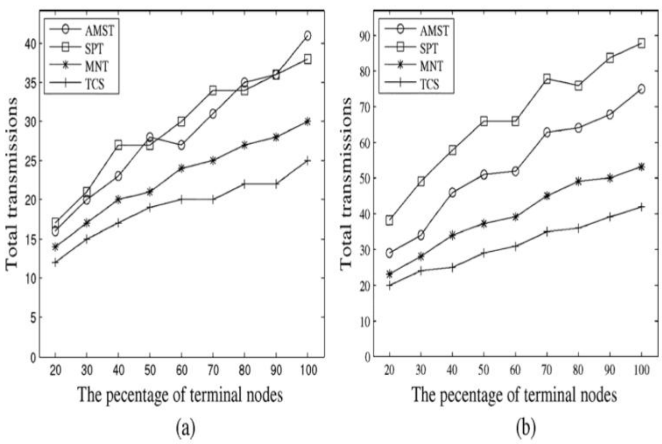

Fig. 4. Performance evaluation of various algorithms for one-to-many multicasting. The percentage of terminal nodes scales from 20% to 100%.
(a) $|V|$= 100. (b) $|V|$=300.

TABLE III
TIME COMPLEXITIES OF DIFFERENT ALGORITHMS

SPT	O($\|V\|^2$)
AMST	O ($\|V\|\log\|V\|+\|E\|$)
MNT	O ($\|V\|^2$)
TCS	O ($\|V\|^2$)

Fig. 4(a) and (b) shows the total number of transmissions in one-to-many multicasting for networks of size 100 and 300, respectively. As promised by its inventors, MNT outperforms SPT and AMST because the multicast tree generated by MNT has less forwarding nodes (non leaf nodes) than the other multicast trees. We also see that TCS significantly outperforms all the other algorithms, and the total number of transmissions can be reduced by about 20% even compared to MNT. The reason is that since the traditional SPT, AMST, and MNT algorithms generate multicast trees regardless of the duty cycles of the wireless nodes, they cannot optimize the transmission schedules of the forwarding nodes in a global manner.

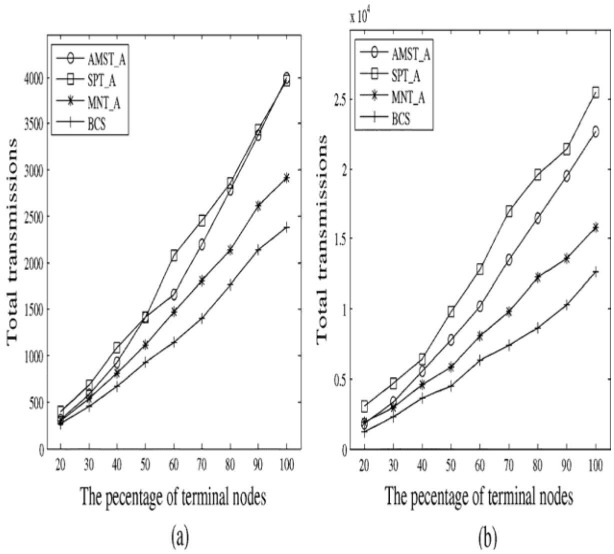

Fig. 5. Performance evaluation of various algorithms for all-to-all multicasting. The percentage of terminal nodes scales from 20% to 100%. (a) $|V|$= 100. (b) $|V|$=300.

In Fig. 5, we evaluate the performance of Algorithm 3 (de-noted by BCS) for all-to-all multicasting. A revised version of the SPT algorithm, namely, SPT A, is used for computing the energy cost of all-to-all multicasting based on a shortest path tree.

The network parameters in Fig. 5(a) and (b) are the same as those in Fig. 4(a) and (b), respectively. It can be seen that the simulation results in Fig. 5 show similar patterns with Fig. 4, and the BCS algorithm again outperforms the other algorithms in terms of the total energy cost. This can be explained by the same reasons that we have described in the one-to-many multicasting case.

B. Simulation Setup

In our network simulations, nodes are uniformly randomly deployed in a 200m x 200m square region with a density of 0.001 nodes/m2. MULEs begin with uniformly random locations, and they move at each time slot according to a Random Direction mobility model. Each MULE randomly selects a speed from [5 m/s, 15 m/s] and a direction from [0, 2π] and moves according to this speed and direction until it reach the network boundary. Each node generates a packet every 10 minutes. We compare the average packet delay and the energy consumed in 2 hours of operation for the WISP-Mote scenario and for the duty cycling scenario.

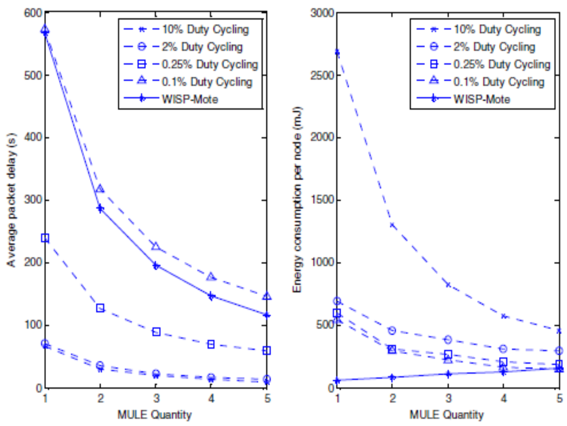

Fig 6: Packet delay and energy consumption comparisons as a function of the number of MULEs.

Fig. 6 shows the results of delay and energy consumption for 0.1%, 0.25%, 2% and 10% duty cycling and for the WISP Mote. Compared to duty cycling, the WISP-Mote has to buffer data for a longer time until a MULE is within its wake-up range, which results in a high packet latency. On the other hand, in the duty cycling scenario, the lower the duty cycle value, the higher the probability of missing a MULE, since the nodes are in sleep mode longer. The resulting delay becomes large for very low duty cycle values (e.g., 0.1%). Therefore, the delay performance of the WISP-Mote is worse than 10%, 2% and 0.25% duty cycling, but it achieves better delay than 0.1% duty cycling. The energy consumption values, provided in Fig. 3, show that the WISP-Mote uses much less energy than 0.1%, 0.25%, 2% and 10% duty cycling, since the WISP-Mote does not waste energy in unnecessary wake-ups and idle listening.

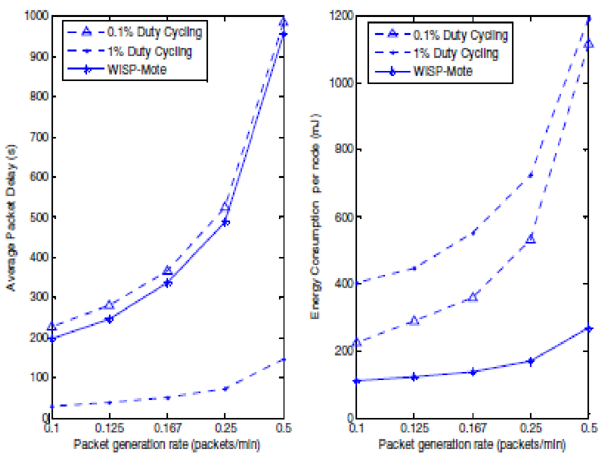

Figure 7. Packet delay and energy consumption comparisons as a function of packet generation rate.

Fig. 7 shows the performance under various traffic loads. We assume only one node is allowed to transmit data to a certain MULE in one time slot and will consume energy in sensing again if the channel is busy. Therefore, increasing the traffic load leads to an increase in delay and energy consumption due to re-sensing the channel. The packet delay caused by re-sensing is not significant compared to the delay due to buffered data. We observe that when the packet generation rate increases from 0.1 packets/min to 0.125 packets/min, the average packet delay of all three scenarios only increased slightly. However, when the packet generation rate increases, the packet delays of 0.1% duty cycling and the WISP-Mote increase exponentially, due to accumulated data in the buffers. In the 1% duty cycling scenario, when packet generation rate is 0.5 packets/min, nodes are still able to deliver packets before new packets are generated. Therefore, the delay is still increased linearly. On the other hand, the energy consumptions in the duty cycling scenarios are dominated by re-sensing the channel when the packet generation rate is increased. The WISP-Mote scenario has less chance of re-sensing due to its limited wake-up range, which results in less energy consumption compared to the duty cycling scenarios.

VII. CONCLUSION

In this paper, we have studied the MEM problem in DC-WSNs. In the case of one-to-many multicasting, we have formalized the MEMTCS problem and proved the NP-hardness of it. A lower bound on the approximation ratio of any polynomial-time algorithm for the MEMTCS problem has been given in our work. In the case of all-to-all multicasting, we have proved that the MEMBCS problem is also NP-hard. We have presented approximation algorithms for the MEMTCS problem and the MEMBCS problem.

We present and characterize a physical implementation of a passive RFID wake-up device using existing hardware. In the Data MULE scenario, the benefit of our device in terms of reducing energy consumption is shown through simulation results. By trading off the extra hardware cost and increased packet latency, the lifetime of the entire network can be greatly extended.

The simulation results have demonstrated that our algorithms outperform other related algorithms in terms of the total transmission energy cost, without sacrificing much of the delay performance. For a similar packet delay performance, a network utilizing WISP-Motes can save up to 89% of the energy consumption compared with 0.1% duty cycling for 1 MULE. To reduce the packet delay and improve the network robustness, multiple data MULEs can be deployed.

Future Scope:

Currently, we are on the way of studying the combination of duty cycling and other energy conservation techniques (e.g., mobile sink [20], data collection [21], [22], and directional sensor/antenna [23]) and propose approximation algorithms for such problems.

REFERENCES

[1] G. Anastasi, M. Conti, M. D. Francesco, and A. Passarella, "Energy conservation in wireless sensor networks: A survey," *Ad Hoc Netw.*, vol. 7, no. 3, pp. 537–568, 2009.

[2] Y. Gu and T. He, "Data forwarding in extremely low duty-cycle sensor networks with unreliable communication links," in *Proc. ACM SenSys*, 2007, pp. 321–334.

[3] J. Hong, J. Cao, W. Li, S. Lu, and D. Chen, "Minimum-transmission broadcast in uncoordinated duty-cycled wireless ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 59, no. 1, pp. 307–318, Jan. 2010.

[4] S. Guo, Y. Gu, B. Jiang, and T. He, "Opportunistic flooding in lowduty- cycle wireless sensor networks with unreliable links," in *Proc. ACM MobiCom*, 2009, pp. 133–144.

[5] L. Su, B. Ding, Y. Yang, T. F. Abdelzaher, G. Cao, and J. C. Hou, "oCast: Optimal multicast routing protocol for wireless sensor networks," in *Proc. IEEE ICNP*, 2009, pp. 151–160.

[6] C. Gui and P. Mohapatra, "Power conservation and quality of surveillance in target tracking sensor networks," in *Proc. ACM MobiCom*,2004, pp. 129–143.

[7] N. Xu, S. Rangwala, K. K. Chintalapudi, D. Ganesan, A. Broad, R. Govindan, and D. Estrin, "A wireless sensor network for structural monitoring," in *Proc. ACM SenSys*, 2004, pp. 13–24.

[8] I. Akyildiz, W. Su,Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *IEEE Commun. Mag.*, vol. 40, no. 8, pp. 102–114, Aug. 2002.

[9] G. Xing,M. Li, H. Luo, and X. Jia, "Dynamic multiresolution data dissemination in wireless sensor networks," *IEEE Trans.Mobile Comput.*,vol. 8, no. 9, pp. 1205–1220, Sep. 2009.

[10] D. Li, Q. Liu, X. Hu, and X. Jia, "Energy efficient multicast routing in ad hoc wireless networks," *Comput. Commun.*, vol. 30, no. 18, pp. 3746–3756, 2007.

[11] W. Liang, "Approximate minimum-energy multicasting in wirelessad hoc networks," *IEEE Trans. Mobile Comput.*, vol. 5, no. 4, pp.377–387, Apr. 2006.

[12] K. Han, L. Xiang, J. Luo, and Y. Liu, "Minimum-energy connected coverage in wireless sensor networks with omni-directional and directional features," in *Proc. ACM MobiHoc*, 2012, pp. 85–94.

[13] A. P. Sample, D. J. Yeager, P. S. Powledge, and J. R. Smith. "Design of an RFID-based battery-free programmable sensing platform," In IEEE Transactions on Instrumentation and Measurement , 2008.

[14] J. Polastre, R. Szewczyk, and D. Culler, "Telos: Enabling Ultra-Low Power Wireless Research", The Fourth International Conference on Information Processing in Sensor Networks: Special track on Platform Tools and Design Methods for Network Embedded Sensors IPSN 2005: 364-369, April 25-27, 2005

[15] R. C. Shah, S. Roy, S. Jain, and W. Brunette, "Data MULEs: modeling a three-tier architecture for sparse sensor networks", Proceedings of the First IEEE. 2003 IEEE International Workshop on (2003), pp. 30-41.

[16] N. Pletcher, S. Gambini, and J. Rabaey, "A 65µW, 1.9 GHz RF to Digital Baseband Wakeup Receiver for Wireless Sensor Nodes," IEEE CICC 2007, San Jose, 16-19 Sept. 2007.

[17] M. J. Miller, and N. H. Vaidya, "Minimizing energy consumption in sensor networks using a wakeup radio", IEEE WCNC, 2004.

[18] P. Le-Huy and S. Roy, "Low-Power Wake-Up Radio for Wireless Sensor Networks," IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, 2008.

[19] L. Gu and J. Stankovic, "Radio-Triggered Wake-up for Wireless Sensor Networks," Real-Time Systems archive. Volume 29, Issue 2-3, March 2005.

[20] J. Luo and J.-P.Hubaux, "Joint sink mobility and routing to increase the lifetime ofwireless sensor networks: The case of constrainedmobility," *IEEE/ACM Trans. Netw.*, vol. 18, no. 3, pp. 871–884, Jun. 2010.

[21] L. Xiang, J. Luo, and A. Vasilakos, "Compressed data aggregation for energy efficient wireless sensor networks," in *Proc. 8th IEEE SECON*, 2011, pp. 46–54.

[22] H. Jiang, S. Jin, and C. Wang, "Prediction or not? An energy-efficient framework for clustering-based data collection in wireless sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 22, no. 6, pp. 1064–1071, Jun. 2011.

[23] K. Han, L. Xiang, J. Luo, and Y. Liu, "Minimum-energy connected coverage in wireless sensor networks with omni-directional and directional features," in *Proc. ACM MobiHoc*, 2012, pp. 85–94.