Towards Energy-efficient Collision-free Data Aggregation Scheduling in Wireless Sensor Networks with Multiple Sinks

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Abstract: Traditionally, Wireless Sensor Networks (WSNs) are deployed with a single sink. Due to the emergence of sophisticated applications, WSNs may require more than one sink, where many nodes forward data to many sinks. Moreover, deploying more than one sink may prolong the network lifetime and address fault tolerance issues. Several protocols have been proposed for WSNs with multiple sinks. However, they are either routing protocols or forward data from *many* nodes to *one* sink. In this paper, we propose data aggregation scheduling and energy-balancing algorithms for WSNs with multiple sinks that forward data from *many* nodes to *many* sinks. The algorithm first forms trees rooted at *virtual sinks* and then balances the number of children among nodes to balance energy consumption. Further, the algorithm assigns contiguous slots to sibling nodes to avoid unnecessary energy waste due to active-sleep transitions. We prove a number of theoretical results and the correctness of the algorithms. Simulation and testbed results show the correctness and performance of our algorithms.

1 INTRODUCTION

A wireless sensor network (WSN) consists of a set of resource-constrained devices, called nodes, that communicate wirelessly via radio. These nodes sense the environment for events of interest and subsequently relay the information to a dedicated device called a *sink*, with data from several nodes aggregated along the way for energy efficiency reasons. The data can then later be analysed offline.

Traditionally, WSNs have been deployed with a single sink (Akyildiz et al., 2002). However, there are several reasons that limit the usefulness of a single sink. For example, the emergence of more sophisticated applications require more than one sink (Mottola and Picco, 2011). Moreover, deploying more than one sink may improve network throughput and prolong network lifetime by balancing energy consumption, and may address fault tolerance issues (Lee et al., 2005; Valero et al., 2012; Sitanayah et al.,).

In WSNs, TDMA-based protocols are often used to avoid message collisions and guarantee timeliness properties. Also, TDMA-based protocols have the advantages of avoiding idle listening and overhearing. TDMA MAC protocols work by breaking the timeline into slots and assigning those slots to nodes. Each node then can only transmit in a slot it has been assigned. Lots of TDMA-based protocols have been proposed (Rajendran et al., 2005; Rajendran et al., 2006; Sohrabi et al., 2000). However, most TDMA-based MAC protocols have been developed with a single sink assumption. In a WSN with multiple sinks, such slot assignment will result in a very high latency for one of the sink.

Thus, this implies that there is a need for TDMA-based MAC protocols specifically for WSNs with multiple sinks. There is a dearth of work in this area.

Data aggregation scheduling (DAS) algorithms in a WSN with *multiple sinks* have been presented in (Kawano and Miyazaki, 2008; Bo and Li, 2011). However, in the works, the data aggregation scheduling is done from *many* nodes to *one* sink, whereas this paper considers the data aggregation scheduling from *many* nodes to *many* sinks.

One way to solve the data aggregation scheduling problem in WSNs with multiple sinks is to first develop a backbone that connects sinks and then allocate slots to nodes that connect to the backbone. The prob-

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lem of developing the backbone, i.e., connecting the sinks is directly related to the problem of developing a Steiner tree (Gilbert and Pollak, 1968). In this case, we are interested in developing a minimum Steiner tree, which is known to be NP-complete (Karp, 1972). To address the computational complexity of this problem, there are different ways of going about it. One of them is to look at specific instances of the problem that can lead to a polynomial-time solution to the problem. In this paper, we focus on the problem with 2 sinks, since the minimum Steiner tree can be computed in polynomial-time, as the minimum Steiner tree is the shortest path between the sinks. However, our proposed algorithm for 2 sinks also works for WSNs with more than 2 sinks, but in sub-optimal ways.

In this context, we make the following novel contributions:

- We formalise the problem of DAS scheduling in a WSN.
- We prove a number of impossibility results, as well as show a lower bound for solving a variant of DAS called weak DAS.
- We propose two algorithms, which taken together, solves weak DAS and results in a schedule that matches the predicted lower bound.
- Through experiments, we show the performance and correctness of the algorithms.

The rest of the paper is organized as follows. In Section 2, we present an overview of related work. In Section 3, we formalise the problem of Data Aggregation Scheduling (DAS) in a WSN. Then, in Section 4, we prove a number of impossibility results, as well as show a lower bound for solving a variant of DAS called weak DAS. Further, in Section 5, we propose two algorithms, called Balancing Tree Formation (BTF) and Energy-Efficient Collision Free (EECF), which taken together, solves weak DAS and results in a schedule that matches the predicted lower bound. In Section 6, we present experimental setup. Finally, in Section 7, through simulations, we show the correctness and performance of our algorithms.

2 RELATED WORK

Protocols that have been developed on communication for WSNs with multiple sinks can be found in(Mottola and Picco, 2011; Kawano and Miyazaki, 2008; Bo and Li, 2011; Thulasiraman et al., 2007; Tuysuz Erman and Havinga, 2010; Hui Zhou and Xu, 2012). A scheme proposed in (Mottola and Picco, 2011) performs data collection from many nodes to many sinks. The main idea of the protocol is to decrease the number of redundant transmission by using information about the neighbours. In (Thulasiraman et al., 2007), authors propose an algorithm that builds two node-disjoint paths from every node to two different (drains) sinks. If one of two paths fails, the other is used to route the data. In (Tuysuz Erman and Havinga, 2010), authors propose a routing protocol that is based on hexagon-based architecture. Nodes in the network is grouped into hexagons according to their locations. A routing protocol proposed in (Hui Zhou and Xu, 2012), is based on trees. In the protocol, different trees rooted at different sinks are used to forward data. These algorithms address the problem at routing level, i.e., none of these schemes provide a MAC layer protocol.

The work presented in (Kawano and Miyazaki, 2008; Bo and Li, 2011) have more relevance to our work. In (Kawano and Miyazaki, 2008), in addition to an algorithm that forms shortest path trees rooted at each sink in a WSN with multiple sinks, authors propose a scheduling algorithm that use a graph colouring algorithm. So, nodes send to their nearest sink without collision. The authors of (Bo and Li, 2011), propose two algorithms for scheduling data aggregation in multiple-sink sensor networks. The first of the algorithm is Voronoi-based scheduling where the sensing area is divided into regions forming k forests, one forest for each sink. Then the algorithm makes schedules for nodes. The second algorithm is Independent scheduling which differs from the first algorithm in forest construction. However, in both of the algorithms different portions of sensor nodes send their data to a *single different* sink, i.e., *many-to-one* communication, whereas we consider the case where *many* nodes send their data to *many* sinks (*many-to-many*).

3 PROBLEM FORMULATION

We present the following definitions that we will use in this paper.

Definition 1 (Schedule). *A schedule $\mathbb{S} : V \to 2^{\mathbb{N}}$ is a function that maps a node to a set of time slots.*

Definition 2 (DAS-label). *Given a network $G = (V,E)$, a sink Δ, a schedule $\mathbb{S}$ and a path $\gamma = n \cdot m \ldots \Delta$, we say that* n is DAS-labeled under $\mathbb{S}$ on γ for Δ *if* $\exists t \in \mathbb{S}(n) \cdot \exists t' \in \mathbb{S}(m) : t' > t$.

We call the node m on γ the Δ-parent of n and γ the DAS-path for n.

Definition 3 (Strong and Weak Schedule). *Given a network $G = (V,E)$, a sink $\Delta \in V$ and a schedule $\mathbb{S}$,*

$\mathbb{S}$ *is said to be a* strong DAS schedule for Δ *for a node* $n \in V$ *iff* $\forall$ *path* $\gamma_i = n \cdot m_i \ldots \Delta$*, n is DAS-labeled under* $\mathbb{S}$ *on* γ_i *for* Δ. $\mathbb{S}$ *is a* weak DAS schedule for Δ *for n if* $\exists$ *path* $\gamma = n \cdot m_i \ldots \Delta$ *such that n is DAS-labeled under* $\mathbb{S}$ *on* γ *for* Δ.

A schedule $\mathbb{S}$ *is strong DAS (resp. weak DAS) for G iff* $\forall n \in V$*,* $\mathbb{S}$ *is strong DAS schedule (resp. weak DAS schedule) for* Δ *for n.*

We will only say a strong or weak schedule whenever Δ is obvious from the context. A strong schedule, in essence, is resilient to problems that occur in the network such as radio links not working or node crashes during deployment. On the other hand, a weak schedule is not resilient and, any problem happening, will entail that a message from node *n* to *m* will be lost.

It has been shown in (Jhumka, 2010) that it is impossible to develop strong schedules.

Given a network with 2 sinks Δ_1, Δ_2, we wish to develop a weak schedule for Δ_1 and Δ_2. There are several possibilities to achieve this. In general, to develop a weak schedule, several works have adopted the approach whereby a tree is first constructed, rooted at the sink, and then slots assigned along the branches to satisfy the data aggregation constraints. A trivial solution is to construct two trees, each rooted at a sink, and then to assign slots to nodes along the trees. This means that nodes can have two slots, i.e., meaning that nodes may have to do two transmissions for the same message. Thus, we seek to reduce the number of slots for nodes to transmit in.

3.1 DAS Scheduling

We model our problem as follows:

We capture slots assignment with a set of decision variables.

$$t_n^{\mathbb{S}} = \begin{cases} 1 & t \in \mathbb{S}(n) \\ 0 & \text{otherwise} \end{cases}$$

A set value assignment to these variables represent a possible schedule. The number of slots used, which equates to the number of transmission by nodes, has to be reduced for extending the lifetime of the network. The number of slots used is given by:

$$numSlots_{\mathbb{S}} = \sum_{t \in T, n \in V} t_n^{\mathbb{S}} \qquad (1)$$

We also capture the number of nodes with multiple slots as follows:

$$f_n^{\mathbb{S}} = \begin{cases} 1 & |\mathbb{S}(n)| > 1 \\ 0 & \text{otherwise} \end{cases}$$

However, such a schedule may not assign a slot to a given node, so we need to rule out some schedules with a constraint:

$$\forall n \in V \cdot \exists t : t_n^{\mathbb{S}} = 1$$

The above constraint means that all nodes in the network will be assigned at least one slot. We also rule out schedules $\mathbb{S}$ that assign the same slot to two nodes that are in the two-hop neighbourhood, i.e,

$$\forall m, n \in V : t_m^{\mathbb{S}} = 1 \wedge t_n^{\mathbb{S}} = 1 \Rightarrow \neg 2HopN(m,n)$$

This can be done by using information about two-hop neighbourhood, and it can be obtained by exchanging messages with neighbours. Finally, we require to generate weak DAS schedules $\mathbb{S}$, i.e.,

$$\forall m \in V \cdot \exists n \in V, (m \cdot n \ldots \Delta_1) : t_m^{\mathbb{S}} = 1 \Rightarrow \exists \tau > t : \tau_n^{\mathbb{S}} = 1$$

$$\forall m \in V \cdot \exists n \in V, (m \cdot n \ldots \Delta_2) : t_m^{\mathbb{S}} = 1 \Rightarrow \exists \tau > t : \tau_n^{\mathbb{S}} = 1$$

Thus, to generate an energy-efficient collision-free weak DAS schedule for both Δ_1 and Δ_2, there are different possibilities. For example, one may seek to minimise *numSlots* to reduce the number of slots during which nodes transmit. Another possibility is to reduce the number of times any node can transmit, in some sort of load balancing. Thus, we solve the following problem, which we call the *EECF-2-DAS* problem (for energy-efficient collision-free 2-sinks DAS):

EECF-2-DAS problem: Obtain an $\mathbb{S}$ such that minimise $\sum_{\forall t} \sum_{\forall n \in V} f_n^{\mathbb{S}}$ subject to

1. $\forall n \in V \cdot \exists t : t_n^{\mathbb{S}} \neq 0$
2. $\forall m \in V \cdot \exists n \in V, (m \cdot n \ldots \Delta_1) : t_m^{\mathbb{S}} = 1 \Rightarrow \exists \tau > t : \tau_n^{\mathbb{S}} = 1$
3. $\forall m \in V \cdot \exists n \in V, (m \cdot n \ldots \Delta_2) : t_m^{\mathbb{S}} = 1 \Rightarrow \exists \tau > t : \tau_n^{\mathbb{S}} = 1$
4. $\forall m, n \in V : t_m^{\mathbb{S}} = 1 \wedge t_n^{\mathbb{S}} = 1 \Rightarrow \neg 2HopN(m,n)$

The EECF-2-DAS problem consists of two subproblems: (i) The first three conditions amount to what we call the *weak DAS problem* and (ii) the fourth condition ensures that any weak DAS schedule is collision-free. Collision freedom is guaranteed by ensuring that no two nodes in a 2-hop neighbourhood share the same slot.

4 THEORETICAL CONTRIBUTIONS

In this section, we investigate how small can the number of nodes with multiple slots be to generate an energy efficient collision-free weak schedule in a network with 2 sinks.

4.1 All Nodes have Multiple Slots ($\sum_{\forall n \in V} f_n^{\mathbb{S}} = |V|$)

A trivial solution to this is as follows: generate two trees, each rooted at a different sink. For sink Δ_1, starting with slot $|V|$, assign, in decreasing order, slots to nodes using BFS. The process is repeated with the other tree rooted at Δ_2. This sets an upper bound for collision-free weak schedules for WSNs.

4.2 Every Node has a Single Slot ($\sum_{\forall n \in V} f_n^{\mathbb{S}} = 0$)

In this section, we seek a lower bound on the number of nodes that can have multiple slots assigned to them. As a starting point, we endeavour to determine whether all nodes can have only 1 slot, and the result is captured in Theorem 1.

Theorem 1 (Impossibility of 1 Slot)**.** *Given a network $G = (V,E)$ with 2 sinks Δ_1, Δ_2, then there exists no weak DAS schedule $\mathbb{S}$ for Δ_1, Δ_2 such that $\sum_{\forall n \in V} f_n^{\mathbb{S}} = 0$*

Proof. We assume there is such a weak DAS $\mathbb{S}$ and then show a contradiction.

Assumptions: We assume a network G with 2 sinks Δ_1, Δ_2, and part of the network is as follows: Focusing on the sink Δ_1 , there is a set H_1 of nodes in its first hop. There is also a set H_2 of nodes in its second hop. We also denote by n_h^1, the node in H_1 with the largest slot number. We also assume, for some set of nodes $H_2' \subseteq H_2$, that all nodes in H_2' have n_h^1 as a Δ_1-parent.

Proof: Since the schedule is weak DAS, then $\forall n \in H_2 \cdot \exists m \in H_1 : \mathbb{S}(m) > \mathbb{S}(n)$[1]. Also, because the schedule is weak DAS, no node in H_2' can be a Δ_2-parent for n_h^1. Thus, there $\exists \eta \in H_2, \eta \notin H_2'$ such that η is a Δ_2-parent for n_h^1 and, given that $\mathbb{S}$ is a weak DAS schedule, then $\mathbb{S}(\eta) > \mathbb{S}(n_h^1)$.

Now, since $\eta \in H_2$, $\exists m' \in H_1, m' \neq n_h^1$ such that m' is a Δ_1-parent for η and, given that $\mathbb{S}$ is a weak DAS schedule, then $\mathbb{S}$(m') > $\mathbb{S}(\eta)$. Since we assumed that n_h^1 has the largest slot in H_1, it implies that $\forall m \in H_2 :$ $\mathbb{S}(n_h^1) > \mathbb{S}(m)$. This also means that $\mathbb{S}(\eta) < \mathbb{S}(n_h^1)$, which contradicts the previous conclusion that $\mathbb{S}(\eta)$ $> \mathbb{S}(n_h^1)$.

Hence, no such $\mathbb{S}$ exists. $\square$

Here, we prove that there exists no algorithm that can generate a weak DAS schedule for both Δ_1 and Δ_2 with all nodes being assigned a single slot. Theorem 1 captures a lower bound for developing a weak DAS schedule for two sinks, in that it means that it is mandatory for some nodes to have at least two slots to solve weak DAS for two sinks.

[1]Since $\mathbb{S}$(n) returns a set, we abuse the notation here for mathematical comparison.

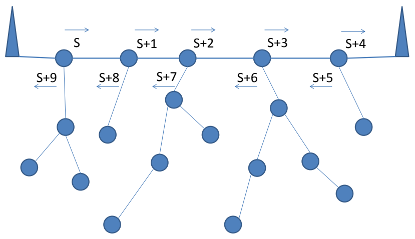


Figure 1: An example of network that solves weak DAS. Arrows show to which sink is used the slot. s is an integer that shows the slot of the node.

4.3 Towards Minimizing ($\sum_{\forall n \in V} f_n^{\mathbb{S}}$)

Having established a condition that there should be a certain number of nodes that require at least two slots, an important question is: how are these nodes with 2 slots chosen from the network?

One way of building a network that solves the weak DAS problem is to assign 2 slots to the nodes on the path that connects Δ_1 and Δ_2 and assign 1 slot to all other nodes like shown in Figure 1. The values $s+i$ in the figure are the time slots of the nodes. The arrows in the figure shows the direction of packets send at time slot $s+i$. In the figure, all nodes send their values to one of the nodes on the path. In turn, the nodes on the path use 2 slots to send their aggregated values to two sinks, one slot for each sink. Thus, the minimum number of nodes with at least two slots that can connect two sinks is captured in the following result (Corollary 1):

Corollary 1. *Given a network $G = (V,A)$ with two sinks Δ_1 and Δ_2, then there exists a weak DAS $\mathbb{S}$ for G, $\sum_{\forall n \in V} f_n^{\mathbb{S}} = l-1$, where l is the length of the shortest path between Δ_1 and Δ_2.*

Since we know that it is possible to obtain a weak DAS schedule $\mathbb{S}$ that assigns two or more slots to at most $l-1$ nodes, the objective is to determine the minimum number of such nodes with at least 2 slots. This is captured in the following result (Theorem 2):

Theorem 2. *Given a network $G = (V,A)$ with two sinks Δ_1 and Δ_2, a path $P = \Delta_1 \cdot n_1 \cdot n_2 \ldots n_{l-1} \cdot \Delta_2$ that is a shortest path between Δ_1 and Δ_2 of length l with $l-1$ nodes and a schedule that DAS-labels all nodes $n_1 \ldots n_{l-1}$ on P and P^r for Δ_2 and Δ_1 respectively, where P^r is the reverse of path P . Then, there exists no weak DAS schedule $\mathbb{S}$ such that $\sum_{\forall n \in V} f_n^{\mathbb{S}} \leq l-3$.*

5 ALGORITHMS

Based on the results developed in Section 4, we develop a 3-stage weak DAS algorithm. The first phase computes a shortest path between the two designated sinks. Every node on the shortest path is considered a *virtual sink*. The second phase consists of each virtual sink constructing a tree that satisfies some property, e.g., balanced tree. This phase is explained in section 5.2.1. The final phase consists in assigning slots to nodes in the network in such a way to satisfy a given property, e.g., minimum latency. This phase will be explained in 5.3.

In this paper, we will focus on the following properties: (i) we develop a balanced tree algorithm such that nodes at a given level spend similar amount of energy and (ii) sibling nodes are allocated contiguous slots so that a parent node does not require switching its radio on and off to capture the data of its children, thereby saving energy (Akyildiz and Vuran, 2010; Shih et al., 2001; Jolly and Younis, 2005).

In the algorithms, we assume that there is no packet loss and no node failures. We plan to work on addressing these problems in the future. We also assume that data packets are assumed to have the same size, and aggregation of two or more incoming packets at a node results in a single outgoing packet. We do not make any assumptions about the network topology.

5.1 Phase 1: Computing the Shortest Path between the Two Sinks

As our results show that a shortest path between the two sinks Δ_1 and Δ_2 is required to minimise the number of nodes with more than a single slot, we first form a shortest path $P = \Delta_1 \cdot v_1 \ldots v_l \cdot \Delta_2$ between Δ_1 and Δ_2. We can obtain such a shortest with a simple distributed shortest path algorithm using *Request* and *Reply* packets, and using hop number as a cost.

After forming P, all nodes on P will take the role of *virtual sink* and set their variables, called *vsink* to 1, and *hop* to 0.

5.2 Phase 2: Developing a Tree Structure

Once a shortest path has been obtained from the first phase, there now exists a set of "virtual sinks" in the network, which we denote by VS. The virtual sinks are nodes that lie along the shortest path. In this phase each of these virtual sinks builds their own tree structure, which can be geared or optimised for a given property. In this section, we propose a balanced tree algorithm (Section 5.2.1), as such a structure enables a balancing of load for nodes at a given level. We also explain another DAS algorithm (Yu et al., 2009), which is cluster-based, against which we compare our results.

5.2.1 Balanced Tree Formation

In this section, we detail the balanced tree formation (BTF) algorithm that we adopt (See Figure 2). When developing the balanced tree, we focus on two main parameters, in the order described: (i) a node chooses a parent based on its (hop) distance from its virtual sink ancestor, in the sense that the node will choose to join a tree where it is closer to a virtual sink, and (ii) if there are competing trees, then a node will join the tree that will make the overall tree structure balanced among the nodes with the same hop distance.

A node can be in one of four states: ALONE, TEMP, JOINED and BALANCE. Initially, all virtual sinks are in the JOINED state, and all other nodes are in the ALONE state. A node goes to the TEMP state when it finds a potential parent with a smaller hop distance. A node goes to the BALANCE state when it finds a potential parent with a smaller number of children. In the TEMP or BALANCE state, a node waits for some time to get a response from the potential parent.

A node n will change its parent from p_1 to p_2 only if

- p_2 has a smaller hop distance (from a virtual sink) than that of p_1
- If both p_1 and p_2 are equidistant to a virtual sink, then n switches parent if p_2 has a smaller number of children.

The first case makes the node have the shortest distance to a virtual sink, and the second case tries to balance the number of children of nodes with the same hop distances.

Informally, the algorithm starts with the virtual sinks broadcasting (i.e., advertising) *JOIN* packets. When a node n_1 receives a *JOIN* packet from a node n_2, it compares its parent hop with the hop of n_2. If the hop of n_2 is smaller, then n_1 requests n_2 to be its parent by sending *REQ* packet, and sets n_2 as its parent if n_1 receives an *ACCEPT* packet from n_2. If the hop numbers are equal and the number of children of n_2 is at least two smaller than the number of children of its current parent, then n_1 requests n_2 to be its parent by sending a *REQ_BAL* packet. If n_1 receives a *BAL_ACCEPT* packet from n_2, it notifies its current parent, by sending a *DISCON* packet, stating that it will connect to another parent. It then sets n_2 as its parent. Whenever n_2 sends *ACCEPT* or *BAL_ACCEPT* to n_1, it adds n_1 to its *children* set.

Whenever a node receives a *DISCON* packet from a node *n*, it removes *n* from its *children* set. When a node stops receiving any packet except *JOIN*, it goes to the *SCHEDULE* state.

In BTF, as mentioned earlier, when selecting a parent, the highest priority is given to a node that have the shortest distance to a virtual sink. If there are more than one potential parent, a priority is given to a node with the smallest number of children in order to balance them. Lemma 1 shows that BTF algorithm correctly achieves this goal.

Lemma 1 (Invariant of BTF). *Given a network $G = (V,A)$ with two sinks Δ_1, Δ_2, then the following is an invariant for the BTF algorithm in Figure 2:*

$\forall m \in V \setminus VS :$

1.$(m.parent \neq \perp \Rightarrow m.hop \neq \infty)$

2.$\wedge (m.hop \leq m.hop')$

3.$\wedge [(m.parent' \neq m.parent) \Rightarrow ((m.hop < m.hop') \vee ((m.hop = m.hop') \wedge (m.parent.numchild < m.parent.numchild')))]$

5.2.2 Cluster-based DAS Scheduling

A tree based DAS scheduling algorithm has been proposed in (Yu et al., 2009), with which we compare our results. The authors, to maximise the benefit from the spatial advantage when allocating slots, build an aggregation tree based on the concept of Connected Dominating Set (CDS). The DAS algorithm adopts the CDS construction algorithm proposed in (Wan et al., 2004) which, in turn, is based on a Maximal Independent Set, with a little modification. Instead of using the original root of the dominating set, they use the sink as the root of the dominating set. For proof of correctness, or otherwise, of the algorithm, we refer the reader to (Yu et al., 2009).

5.3 Phase 3: Slot Allocation for DAS Scheduling

Once the virtual sinks are obtained (phase 1) and each one has its own tree structure (phase 2), every node will identify its *children*, *parent* and *hop*. Also, a node will determine whether it is a virtual sink through the variable *vsink*. If $vsink = 1$, then the node is a virtual sink.

5.3.1 Enery-Efficient Collision Free (EECF) DAS Algorithm for Balanced Tree

In this section, we propose a DAS algorithm that leverages the balanced tree obtained (see Section 5.2.1). To make the DAS energy-efficient, we seek to assign contiguous slots to children so that a parent does not need to continuously sleep and wake-up to collect data as this leads to unnecessary energy usage (Akyildiz and Vuran, 2010; Shih et al., 2001; Jolly and Younis, 2005). Further, since the tree is balanced (at a given level), then nodes at that level spend comparable amount of energy.

We propose a weak DAS algorithm that works in a greedy fashion (See Figure 3). In the algorithm, every node maintains variables *maxslot* and *minslot*. These variables are used to tell neighboring nodes that its children are assigned to the slots starting from *maxslot* down to $minslot + 1$. This allows every node's children to have contiguous time slots. The algorithm uses a special packet called *SLOT* which includes 9 variables necessary for scheduling.

Informally, the scheduling algorithm starts by assigning a time slot to the virtual sink v_1 that is a neighbor of, without loss of generality, Δ_1. As we have proved, there should exist at least $l-2$ nodes with at least two slots. Thus, all nodes except v_1 will be assigned two different slots. The time slot that will be assigned to v_1 is $|V|$. If another virtual sink $v_i, i \neq 1$ receives a *SLOT* packet from v_{i-1}, it sets its first slot to 1 less than the *first* slot of v_i and second slot to 1 more than the *second* slot of v_i, and then broadcasts a *SLOT* packet. The *maxslots* of virtual sinks are assigned to 2 less than their *first* slots (it is 2 less because the next smaller slot is reserved for the next virtual sink), and the *minslots* to the differences of *maxslots* and their number of children. If a node n_1 receives a *SLOT* packet from n_2 or v_i, n_1 sets its slot to the difference of sender's *maxslot* and *rank* of n_1, and then broadcasts a *SLOT* packet. We assume that nodes know their *ranks* before we run the scheduling algorithm. A node can learn its rank in two ways: 1) the parent node may compute and send the rank to its children or 2) the parent node broadcasts IDs of its children and then children computes their ranks themselves.

If a node detects a slot conflict, depending on the *priority*, which is basically the hop distance, slot and rank in that order, the node decides whether to change the slots of its children. And this makes the scheduling collision-free. A node n_1 tells its children to change their slots if

- n_1 finds a neighboring node n_2 that share the same slot with its child and n_2 has a smaller or equal hop distance to n_1's hop distance.
- n_1 finds a neighboring node n_2 that share the same slot with its child and n_2's parent slot is bigger than n_1's slot.
- one of n_1's child *ch* tells to change because *ch* share the same slot with a child of n_2 that has bigger slot than n_1's slot. The variable *otherslot* is used for this purpose.

```
**Process** $i$

**Variables of** $i$
$state \in$ {ALONE, TEMP, JOINED, BALANCE, SCHEDULE}; **Init:** ALONE
$hop, j \in \mathbb{N}$; **Init:** $j := 0$; $hop := \infty$
$parent$: 2-tuple $\langle id, numchild \rangle$; **Init:** $\perp$
$children : \{id : id \in \mathbb{N}\}$ ; **Init:** $\emptyset$
$JOIN, ACCEPT, REQ, REQ\_BAL, BAL\_ACCEPT, BAL\_DENY, DISCON$: Packet types
**Constants of** $i$
$threshJ$
% After forming a shortest path between $\Delta_1$ and $\Delta_2$, every node on the shortest path enters the JOINED state and starts to broadcast a JOIN packet.

**state=ALONE**
upon rcv $\langle JOIN, n, n\_hop, n\_numchild \rangle$
    if ($n\_hop+1 < hop$)
        $state$:=TEMP
        send($REQ, n$)
**state=TEMP**
upon rcv $\langle ACCEPT, n, i, n\_hop, n\_numchild \rangle$
    $parent.id$:=$n$
    $parent.numchild$:=$n\_numchild$
    $hop$:=$n\_hop+1$
    $state$:=JOINED
**state=BALANCE**
upon rcv $\langle BAL\_ACCEPT, n, i, n\_hop, n\_numchild \rangle$
    send(DISCON, $i, parent.id$)
    $parent.id$:=$n$
    $parent.numchild$:=$n\_numchild$
    $hop$:=$n\_hop+1$
    $state$:=JOINED

upon rcv $\langle BAL\_DENY, n, i \rangle$
    $state$:=JOINED
**state=JOINED**
while($j < threshJ$)
    bCast($JOIN, i, hop, |children|$)
    $j := j+1$
    if($j = threshJ$)
        $state$:=SCHEDULE   % See Fig. 3
    endif
upon rcv $\langle JOIN, n, n\_hop, n\_numchild \rangle$
    if($parent.id = n$)
        $parent.numchild$:=$n\_numchild$
        $hop := n.hop+1$
    endif
    if ($n\_hop+1 < hop$)
        $state$:=TEMP
        send($REQ, i, n$)
    elseif($n\_hop+1 = hop \wedge parent.numchild - n\_numchild \geq 2$)
        $state$:=BALANCE
        send($REQ\_BAL, i, n, parent$)
    endif
upon rcv $\langle REQ, n, i \rangle$
    send($ACCEPT, i, n, hop, |children|$)
    $children$:=$children \cup \{n\}$
    $j := 0$
upon rcv $\langle REQ\_BAL, n, i, n\_parent \rangle$
    if($n\_parent.numchild - |children| \geq 2$)
        $children$:=$children \cup \{n\}$
        send($BAL\_ACCEPT, i, n, hop, |children|$)
    else
        send($BAL\_DENY, i, n$)
    endif
    $j := 0$
upon rcv $\langle DISCON, n, i \rangle$
    $children$:=$children \setminus \{n\}$
    $j := 0$
```

Figure 2: Balanced tree formation algorithm.

After all the nodes are assigned their slots, all nodes' slot values are sent to Δ_1 where it computes the minimum of the slots, and broadcasts that value to the nodes. The nodes after receiving the minimum value can compute their slots by taking the difference of its slot and the minimum value, and adding 1. The following Lemma 2 and Theorem 3 prove the correctness of EECF.

Lemma 2 (Invariant of EECF). *Given a network $G = (V, A)$, with a set of virtual sinks $VS \subset V$ that link 2 sinks Δ_1, Δ_2, then the following is an invariant of EECF-DAS:*

$\forall m \in V$ ::

$I0\ m.slot \neq \infty \wedge m.slot2 \neq \infty \Rightarrow m.vsink$

$I1 : \wedge\ m.slot \neq \infty \wedge m.slot2 = \infty \Rightarrow \neg m.vsink$

$I2 :\ \wedge\ m.slot < m.slot' \Rightarrow m.slot < m.parent.slot$

$I3 :\ \wedge\ (m.slot \neq m.slot') \Rightarrow (\exists n \in 2HopN(m) \cdot m.slot' = n.slot') \vee (\exists y \cdot y.parent = m.parent : y.slot' = n.slot')$

Theorem 3. *Given a network $G = (V, A)$ with 2 sinks Δ_1, Δ_2, then (BTF ; EECF-DAS) solves the EECF-DAS problem with a schedule $\mathbb{S}$ s.t. $\sum_{n \in V} f_n^{\mathbb{S}} = l - 2$, where l is the length of the shortest path between Δ_1 and Δ_2.*

Proof. Follows directly from Lemmas 1 and 2. □

6 SIMULATION SETUP

We perform TOSSIM (Levis et al., 2003) simulations to evaluate our EECF-DAS algorithm. We evaluated it on networks of sizes 400, 600, 800 and 1000 nodes with transmission ranges of 10m, 15m and 20m. The nodes were uniformly randomly distributed on a 100m×100m surface. The two sinks were deployed at two diagonally opposite corners of the region.

To confirm the consistency of simulation results, we also ran the EECF-DAS algorithm on Indriya testbed (Doddavenkatappa et al., 2011). We select the node with ID = 1 as sink 1 and ID = 46 as sink 2. To increase the diameter (largest hop number) of the network, we set the transmission power to 7. The number of hops between sink 1 and sink 2 is 5.

To compare the performance of EECF-DAS with the cluster-based DAS (CDAS) protocol proposed in (Yu et al., 2009), we also simulated EECF-DAS and CDAS (See 5.2.2) in Java. We used Java because in (Yu et al., 2009), authors have not clrealy stated how a node communicate with a node in its competitor set, and they simulated CDAS using C++. We chose CDAS because it is claimed to be one of the algorithms with the lowest latency. However, as

```
Process i
Variables of i
$slot, slot2, maxslot, minslot, otherslot, parentslot, s, x \in \mathbb{N}$; Init: $slot, slot2, maxslot, minslot, otherslot, parentslot := \infty$;    $s, x := 0$
$vsink \in \{0,1\}$ %vsink=1 if i is a virtual sink
$rank(id)$: a function that returns the number of greater or equal values to id in children of id's parent.
$P$ : 9-tuple $\langle id, hop, slot, slot2, maxslot, minslot, otherslot, parentslot, vsink \rangle$
$SLOT$: Packet type
Constants of i
threshS
% When the neigbouring virtual sink of $\Delta_1$ enters the SCHEDULE state, it sets its $slot, slot2 := |V|$ and starts    broadcast$(SLOT, threshS)$
```

```
Import from BTF % Import the variables of BTF (Fig 2)
state=SCHEDULE
1 upon rcv$\langle SLOT, \alpha : P \rangle$
 % If the src and i are virtuals sinks and i has not assigned a slot yet, set states accordingly
2   if$(slot = \perp \wedge vsink = 1 \wedge \alpha.vsink = 1)$
3       $slot := \alpha.slot - 1$
4       $slot2 := \alpha.slot2 + 1$
5       $maxslot := slot - 2$
6       $minslot := maxslot - |children|$
7       broadcast$(SLOT, threshS)$
 % If the src is the parent of i and src's maxslot has been changed, set states accordingly
8   elseif$(parent.id = \alpha.id)$
9       $parentslot := \alpha.slot$
10      if$(slot \neq \alpha.maxslot - rank(i))$
11          $slot := \alpha.maxslot - rank(i)$
12          $maxslot := slot - 1$
13          $minslot := maxslot - |children|$
14          broadcast$(SLOT, threshS)$
 % If the src is a potential parent
15  elseif$(\alpha.hop = hop - 1)$
   % If i has the same slot as a child of src and src's slot is larger than i's parent slot, or they are
equal and src's id is larger than i's parent id, then notify i's parent about this (See lines 31-36)
16      if$((\alpha.slot > parentslot \vee (parentslot = \alpha.slot \wedge \alpha.id \geq parent.id))$
17                      $\wedge (\alpha.maxslot \geq slot \wedge slot > \alpha.minslot))$
18          $otherslot := \alpha.minslot$
19          broadcast$(SLOT, threshS)$
   % If one of i's children shares the same slot with the potential parent, set states of i accordingly

20      elseif$(maxslot \geq \alpha.slot \wedge \alpha.slot > minslot)$
21          $maxslot := \alpha.slot - 1$
22          $minslot := maxslot - |children|$
23          broadcast$(SLOT, threshS)$
24      endif
 % If i's and src's hops are equal and one of i's child shares
 % the same slot with the src, set states of i accordingly
25  elseif$(\alpha.hop = hop)$
26      if$(maxslot \geq \alpha.slot \wedge \alpha.slot > minslot)$
27          $maxslot := \alpha.slot - 1$
28          $minslot := maxslot - |children|$
29          broadcast$(SLOT, threshS)$
30      endif
 % If the src is a child of i and has detected a collision, then set states of i accordingly
(See lines 16-19)
31  elseif$(\alpha.id \in children)$
32      if$(\alpha.otherslot < maxslot)$
33          $maxslot := \alpha.otherslot$
34          $minslot := maxslot - |children|$
35          broadcast$(SLOT, threshS)$
36      endif
 % If the hops of src and i's children are equal and a child of i shares the same slot
with the src and i's slot is smaller than src's parent slot or, if the slots are equal, i's id
is smaller than src's parent id, then set states of i accordingly
37  elseif$(\alpha.hop = hop + 1)$
38      if$((\alpha.parentslot > slot \vee (\alpha.parentslot = slot \wedge \alpha.id > i)) \wedge$
39                      $(\alpha.slot \leq maxslot \wedge \alpha.slot > minslot))$
40          $maxslot := \alpha.slot - 1$
41          $minslot := maxslot - |children|$
42          broadcast$(SLOT, threshS)$
43      endif
44  endif

broadcast$(SLOT, x)$
1   $s := 0$
2   while$(s < x)$
3       bCast$(SLOT, \alpha : P)$
4       $s := s + 1$
```

Figure 3: Data aggregation scheduling algorithm.

CDAS was intended for a network with only one sink, we adapted it to make it work in a network with two sinks.

For comparison purposes, we adapted CDAS into two different ways: i) we ran DAS twice, one for each sink, and called this adapted algorithm 2DAS, and ii) we first run a shortest path algorithm to form a shortest path (as in EECF) between the two sinks and, instead of assigning Δ_1 as the root of the dominating tree, as in (Wan et al., 2004), we assigned each virtual sink (a node on the shortest path) as a root of a dominating tree and called this adapted algorithm SP-DAS. We ran each case ten times and computed the average.

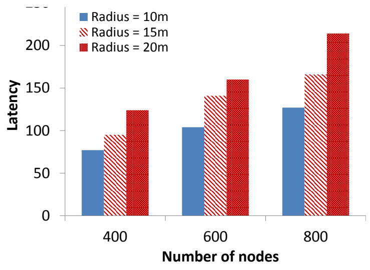
We compared the latency, which is equal to the largest slot of the nodes in the network, and the number of slots each node should be awake to transmit and receive.

7 RESULTS

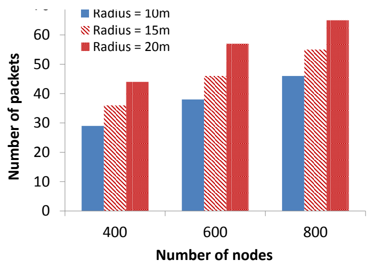
Figure 4 shows the latency and the number of packets transmitted to complete the scheduling when simulated with TOSSIM. In Figure 4(a), the average latency is shown. We can see that the latency is low, although EECF considers contiguousness of slots. Also we see that the latency is directly related to the neighborhood size/network density. Figure 4(b) shows the average number of packet transmissions per node to complete the scheduling. From the figure we see that it increases linearly as the neighborhood size/network density increases.

As expected, in general, the algorithms that use the shortest path as a backbone show good results. From the figure 5(a) we can see that the latencies of EECF and SP-DAS can be two times lower than that of 2DAS. The figure 5(b) shows the number of children of networks constructed by EECF, SP-DAS and 2DAS. As can be observed, 2DAS has more nodes that have large number of children, which implies that nodes in 2DAS should be awake more time slots than EECF and SP-DAS.

Figures 6(a) and 6(b) show the transmission and reception time slots of the 15 nodes of EECF, 2DAS and SP-DAS with the maximum number of slots. From the figure we can see that EECF's reception slots are contiguous while 2DAS's and SP-DAS's reception slots are usually separated. It can also be observed that the nodes scheduled with EECF needs to

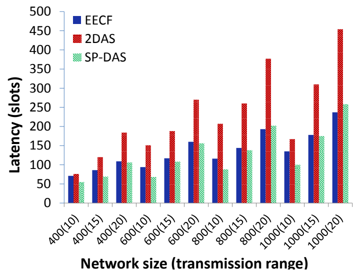


(a) The average latency.

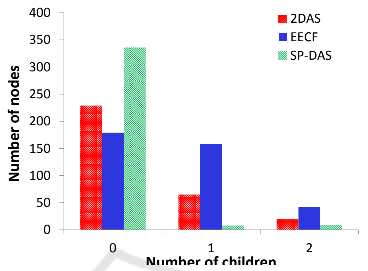


(b) The number of packet transmissions per node.

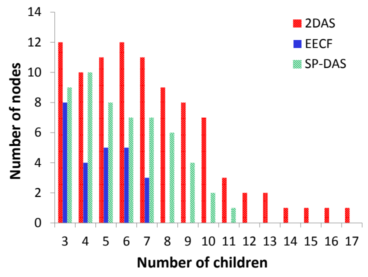
Figure 4: The average latency and number of packet transmissions with different network sizes (EECF).



(a) The latencies with different network sizes and transmission ranges

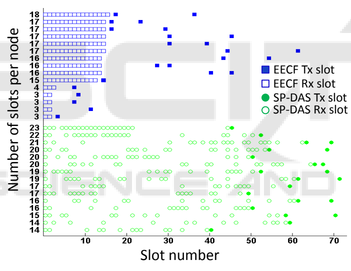


(b) The number of nodes with 0,1 and 2 children.

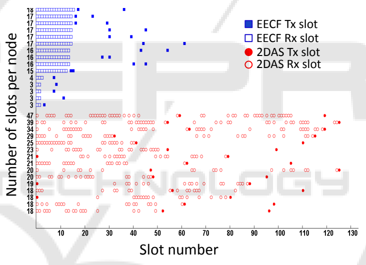


(c) The number of nodes with ≥3 children.

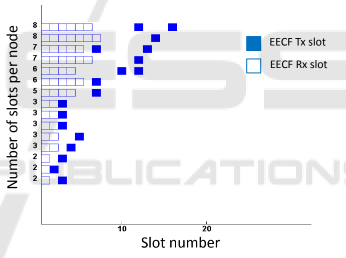
Figure 5: Comparison of EECF, SP-DAS and 2DAS.



(a) The number of slots per node



(b) The number of slots per node



(c) The number of slots per node

Figure 6: (a) and (b)Comparison of EECF, SP-DAS and 2DAS (400 nodes, transmission range=15m), (c) Testbed results.

switch from the *sleep* to the *active* mode at most 3 times. While in 2DAS and SP-DAS the number of switches could be large and can alternate every slot. From the figure we can see that in SP-DAS and 2DAS the maximum number of switches is 13 and 20 respectively. This shows that EECF is more energy efficient as nodes in EECF should be awake fewer time slots and make fewer sleep-active switches. Figure 6(c) shows the results obtained from the testbed experiments which confirm that the algorithm assigns contiguous slots to nodes.

As EECF and SP-DAS use a shortest path in their aggregation tree, the number of nodes with 2 transmission slots are equal. However, in the figure, there are 9 nodes in EECF and only 7 nodes in SP-DAS with 2 transmission slots. It is because in SP-DAS there could be nodes that have more children than that of the nodes on the shortest path. From the figure 5(a) we can also see that, in general, SP-DAS has a bit lower latency than EECF.

8 CONCLUSION

In this paper, we proposed two algorithms that balance energy consumption among nodes and schedule data aggregation. We proved a number of theoretical results and the correctness of the algorithms. Experimental results showed the performance of the algorithms, and supported the correctness of our algorithms. To the best of our knowledge, this is the first work that deal with the data aggregation scheduling problem in WSNs with more than one sink where many nodes send data to many sinks.

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