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Many-to-Many Data Aggregation Scheduling in Wireless Sensor Networks with Two Sinks

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Abstract

Traditionally, wireless sensor networks (WSNs) have been deployed with a single sink. Due to the emergence of sophisticated applications, WSNs may require more than one sink. 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, most of them are routing protocols. Differently, our main contribution, in this paper, is the development of a distributed data aggregation scheduling (DAS) algorithm for WSNs with two sinks. We also propose a distributed energy-balancing algorithm to balance the energy consumption for the aggregators. The energy-balancing algorithm first forms trees rooted at nodes which are termed *virtual sinks* and then balances the number of children at a given level to level the energy consumption. Subsequently, the DAS algorithm takes the resulting balanced tree and assigns contiguous slots to sibling nodes, to avoid unnecessary energy waste due to frequent active-sleep transitions. We prove a number of theoretical results and the correctness of the algorithms. Through simulation and testbed experiments, we show the correctness and performance of our algorithms.

Keywords: Wireless sensor networks, Data aggregation scheduling, Two sinks, Many-to-many communication, Medium access control

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1. INTRODUCTION

A wireless sensor network (WSN) consists of a set of resource-constrained nodes, that communicate wirelessly. These nodes sense the environment for events of interest and subsequently relay the information to a dedicated device called *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 [1]. However, there are several reasons that limit the usefulness of a single sink. The emergence of more sophisticated applications, such as Heating, Ventilation, and Air Conditioning (HVAC) systems [28], requires WSNs with more than one sink. Moreover, the deployment of more than one sink may improve the network throughput and prolong network lifetime by balancing energy consumption,

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and may address fault tolerance issues [25, 42, 36].

WSNs are typically resource-constrained networks, with nodes having limited computational and energy resources. To reduce energy consumption, various approaches exist, such as duty-cycling and the use of appropriate medium access control (MAC) protocols. Major sources of energy waste at the MAC layer are:

- Message collisions, which require the retransmission of the collided packets,
- Message overhearing, where a node receives a message meant for another node, and
- Idle listening, which means that a node keeps on listening for messages on an otherwise idle channel [44].

To address the above problems, a typical solution is to use a Time Division Multiple Access (TDMA) based MAC protocol. TDMA MAC protocols work by dividing time into slots and assigning those slots to nodes. Each node can then only transmit in a slot to which it has been assigned. Several TDMA-based MAC protocols have been proposed for WSNs, e.g., [31, 32, 37]. However, most of them have been developed for a WSN with a single sink. Thus, there is a need for TDMA-based MAC protocols specifically designed for WSNs with multiple sinks. However, there is a dearth of work in this area. Data aggregation scheduling (DAS) algorithms in a WSN with *multiple sinks* have been presented in [21, 3]. However, in these works, the data aggregation scheduling is done from *many* nodes to *one* sink which collects all the messages, whereas this work considers data aggregation scheduling from *many* nodes to *many* sinks, where every sink has to collect all messages.

The way we propose to solve the data aggregation scheduling problem in WSNs with two sinks is to first develop a *backbone* that connects the two sinks and then allocate slots to nodes that connect to the backbone. The problem of developing the backbone, i.e., a path connecting the sinks, is directly related to the problem of developing a (minimum) Steiner tree [11], which is a well-studied combinatorial optimization problem. Given a graph $G = (V, E)$ with weighted edges and a set of nodes $S \subseteq V$, a Steiner tree T interconnects all elements in S such that the sum of the edge weights in T is minimal. In the general case, this is an NP-complete problem [20]. The minimum Steiner tree problem can be seen as a combination of computing shortest paths and of computing spanning trees. If the number of vertices to be joined is two, then we only need to compute the shortest path. On the other hand, if all the vertices are involved, then a spanning tree is computed. In this paper, as we focus on two sinks, we will construct a shortest path, which can be achieved in polynomial-time.

In this context, we make the following novel contributions:

- In Section 4, we formalise the problem of DAS scheduling in a WSN with two sinks, where data needs to reach both sinks.
- In Section 5, we prove an impossibility[1] result, as well as derive a lower bound for solving weak DAS, a special case of DAS.

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[1] This means that a given problem cannot be solved deterministically.

- In Section 6, we propose two algorithms which, taken together, solve weak DAS for two sinks. The output of the combined algorithms is a schedule that matches the predicted lower bound.
- Through both simulation and testbed experiments, we show the performance and correctness of the algorithms in Section 8.

The other parts are as follows: In Section 2, we present an overview of related work. We present the formal basis of our work in Section 3. In Section 7, we present the experimental setup. We conclude the paper in Section 9.

2. RELATED WORK

A data aggregation technique is used in data gathering in WSNs to reduce energy consumption, as it reduces the number of transmissions [22]. A number of data aggregation protocols have been proposed in the literature [14, 45, 34, 12, 47, 23, 38, 27]. The routing structure of these protocols could be tree-based [38, 34, 12, 23], cluster-based [14, 45], chain-based [27], and grid-based [19, 30]. However, these protocols have been proposed for WSNs with a single sink. Although our proposed protocol is developed for WSNs with two sinks, the routing structure of our proposed protocol is based on a tree structure.

Protocols that have been developed for communication in WSNs with multiple sinks can be found in [5, 28, 21, 3, 39, 41, 48, 6, 13, 24]. The authors of [5] developed an algorithm where a node chooses a sink in a multi-sink WSN to send its data in such a way that it minimizes energy consumption. A scheme proposed in [28] performs data collection from many nodes to many sinks, i.e., many-to-many communication. The main idea of the protocol is to reduce the number of redundant transmissions by leveraging neighbourhood information. An algorithm that builds two node-disjoint paths from every node to two different sinks was proposed in [39]. If one of the two paths fails, the other path is used to route the data. In [41], the authors propose a routing protocol that is using a hexagon-based architecture. The nodes in the network are grouped into hexagons, based on their locations. The routing protocol proposed in [48], is based on trees. In the protocol, different trees rooted at different sinks are used to forward data. The authors of [6] have proposed an online algorithm for data collection in WSNs with multiple sinks, where sinks are deployed in a stepwise fashion during network operation. In [29], the authors present different routing schemes that are based on a logical tree structure, which is built based on the residual energy of each node. One of these schemes uses a secondary sink to maximize the network lifetime. A data reporting algorithm used for object tracking in multi-sinks WSNs was presented in [10]. The algorithm attempted to reduce energy consumption and balance the load among sinks and nodes.

The works presented in [21, 3, 13, 24] are more closely related to the work presented in this paper. In [21], in addition to an algorithm that computes the shortest-path trees rooted at each sink in a multi-sinks WSN, the authors proposed a scheduling algorithm that uses a graph colouring technique. Then, a node will send messages to its nearest sink in a collision-free fashion. The authors of [3] proposed two algorithms for scheduling data aggregation in multi-sinks WSNs. One of the algorithms is a Voronoi-based scheduling algorithm, where the sensing area is divided into regions to form k forests, one forest for each sink. Subsequently, the algorithm computes the schedules for the nodes. In [13] and [24], the authors proposed cross-layer schemes that consider the routing as well as the MAC layer to maximize the network lifetime and reduce the latency respectively. Most of the above protocols either developed appropriate routing protocols for multi-sinks WSNs or the techniques involved a subset of the nodes forwarding messages to a single sink only. In contrast, we consider the case where *many* nodes send their data to *two* sinks, which is an instance of many-to-many communication.

3. SYSTEM MODEL

We provide the necessary formal background, including the models we use, the syntax we use to write the algorithms and the associated semantics, the computation and communication models.

3.1. Topology and processes

Communication in WSNs is typically modeled a circular communication range centered on a node, and it is typically assumed that all nodes have the same communication range. With this model, a node is thought to be able to directly exchange data with all devices within its communication range. In graph-theoretic terms, we represent a WSN as a *undirected* graph $G = (V, E)$ with a set V of vertices representing the nodes, and a set E of edges (or links) representing the communication links between pairs of nodes. A path between two nodes n_1 and n_i is a sequence of nodes $\gamma = n_1 \cdot n_2 \ldots n_i$ such that $\forall j, 1 \leq j < i, (n_j, n_{j+1}) \in E$. We assume a network where no node has both sinks as neighbours. We also assume that the network topology remains constant, i.e., there is no node crash and no link failure.

A program consists of a finite set of processes. Each process contains a finite set of variables, each taking values from a given finite domain, and a finite set of actions. An assignment of values to variables is called a state and the set of value assignments denote the state space of the program. A predicate defines a set of states, such that the predicate evaluates to *true* in these states.

3.2. Program syntax and semantics

We write programs in a style similar to the guarded command notation [7]. An action has the form

```
state = X
        upon⟨guard⟩
                command
```

The program is written in such a way that it encodes an automaton that captures the execution of the program. The *state* variable indicates the (automaton) state the program is in, i.e., (X) (which we refer to as the Astate), while the general program state (including the value of *state*) is referred to as the program state (or state). In a given state, the *guard*, which is a predicate defined over the set of variables of a process, is evaluated. If it is true, then the corresponding *command* is executed. When the command is executed, the state of the program changes. If the *state* variable changes too, then the *Astate* of the program changes. When the guard is true, then we say that the action is enabled. A process is enabled in a state s when at least one of its guards is enabled in s.

A *command* is a sequence of assignments and branching statements. A guard or command can contain universal or existential quantifiers of the form: $\langle quantifier\rangle\langle boundvariables\rangle : \langle range\rangle : \langle term\rangle$, where *range* and *term* are Boolean constructs. A special **timeout**(*timer*) guard evaluates to true when a *timer* variable reaches zero. A **set**(*timer*, *value*) command sets the timer variable to a specified value.

We choose this programming style for several reasons. First, it is usually simpler to formally reason on a program execution in terms of what guards become true at a given point (i.e., state) in the execution, rather than following a specific control flow. Moreover, representing a program as such makes programs more compact, compared to the more traditional state transition or procedural representations. Finally, this notation matches the programming style of many WSN software platforms, which tend to be event driven [15]. In these cases, the binding of events to their handlers[2] is, in a sense, corresponding to the evaluation of guards.

The execution of a command of a program $\mathcal{A}$ causes the program to update one or more variables and moves the program from one state to another in *one atomic step.* In a given state s, several processes may be enabled, and a decision is needed about which one(s) to execute. The subset of processes that take a step when possible is chosen according to different scheduling policies. To ensure the system makes progress, a notion of fairness is also required. Whenever any of the enabled processes can take a step independent of all others, that is, a continuously enabled action is eventually executed, we say the system is weakly fair [9] and runs in an *asynchronous* manner. This entails there is *no bound* on relative process speeds and message transmission time.

3.3. Communication

Each process is linked with an (auxiliary) *channel* variable, denoted by *ch*, modeling a FIFO queue of incoming messages sent by other processes. The domain of the *ch* variable is the set of (possibly infinite) message sequences. An action with a **rcv**(*msg*,*sender*) guard is enabled when there is a message at the head of the channel variable *ch* of a process. Executing the corresponding command causes the message at the head of the channel to be dequeued, while *msg* and *sender* are bound to the content of the message and the sender identifier. Differently, the **send**(*type*,*src*, *dest*, *msg*) command causes the message *msg* to be attached to the tail of the channel variable *ch* of process(es) in the *dest* set. To capture the broadcast multi-hop nature of WSNs, we extend the semantics of **send** with a **bcast** command, with the following syntax: **bcast**(*type*, *msg*). The **bcast** command causes the *msg* to be simultaneously appended to the tail of the channel variable of all nodes that are within the communication range of the sender. We assume communication to be reliable, i.e., channels always deliver messages placed on them.

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[2] When an event occurs, a related routine, i.e., a handler, is executed, similar to interrupt handlers.

4. PROBLEM FORMULATION

We present the following definitions that will be used 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 (represented as natural numbers).*

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. A node is DAS-labeled if its parent is assigned at least a later time slot, i.e., a slot with higher value.

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 w.r.t. 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 w.r.t. 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*.*

The difference between a weak and a strong DAS schedule is that a weak DAS schedule requires a node to be DAS-labeled w.r.t to a single path to the sink whereas a strong one requires a node to be DAS-labeled for every path. 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 unreliable radio links or node crashes during deployment. On the other hand, a weak schedule is not resilient and, any problem happening, will entail that a message between two neighbour nodes may be lost.

It has been shown in [17] that it is impossible to develop strong schedules. Given a network with 2 sinks Δ_1, Δ_2, we then 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.

4.1. DAS Scheduling

We capture slots assignment with a set of decision variables.

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

The decision variable $t_n^{\mathbb{S}}$ is set to 1 if slot t is one of the assigned slots to node n under schedule $\mathbb{S}$. A set of value assignment to these variables represent a possible schedule. The number of slots used, which is equal 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:

$$numSlots_{\mathbb{S}} = \sum_{t \in \mathbb{N}, n \in V} t_n^{\mathbb{S}}. \tag{1}$$

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

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

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

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

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,

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

where $2HopN(m, n)$ returns true if m and n are in each other's two-hop neighbourhood. 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.,

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

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

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. We solve the following problem, which we call the *EECF-2-DAS* problem (for energy-efficient collision-free 2-sinks DAS):

EECF-2-DAS optimization 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* for two sinks and (ii) the fourth condition ensures that any weak DAS schedule is collision-free.

5. FINDING LOWER AND UPPER BOUNDS

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

5.1. 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 every node can have only a single 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.

Given a network G with 2 sinks Δ_1, Δ_2, we have part of the network as follows: Focusing on the sink Δ_1, there is a set H_1 of nodes one hop away from it. There is also a set H_2 of nodes two hops away from it. 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.

Since the schedule is weak DAS, then $\forall n \in H_2 \cdot \exists m \in H_1 : \mathbb{S}(m) > \mathbb{S}(n)$[3]. 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 $\forall m \in H_2 : \mathbb{S}(n_h^1) > \mathbb{S}(m)$.

---

[3] Since $\mathbb{S}$(n) returns a set, we abuse the notation here for mathematical comparison. It means $\exists s, t \cdot s \in \mathbb{S}(m), t \in \mathbb{S}(n) : s > t$

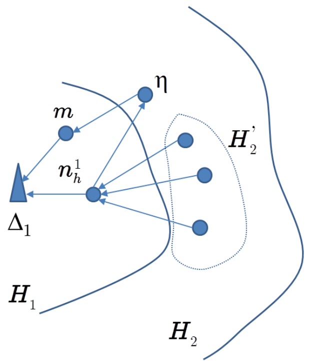


Figure 1: An illustration of the proof of Theorem 1

This also means that $\mathbb{S}(\eta) < \mathbb{S}(n_h^1)$, which contradicts the previous conclusion that $\mathbb{S}(\eta) > \mathbb{S}(n_h^1)$. See Figure 1 for illustration.

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

Therefore, we have proved 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.

5.2. Towards Minimizing $\sum_{\forall n \in V} f_n^{\mathbb{S}}$

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

Our approach to generating a schedule for two sinks is to first develop a network backbone and then to subsequently perform slot assignment. As the problem is related to the Steiner Tree problem, we only require to develop a backbone between the two sinks, which in this case is the shortest path between the two sinks. Thus, one way of building a network that solves the weak DAS problem for a two-sink WSN is to assign 2 slots to the nodes on the shortest path that connects Δ_1 and Δ_2 and possibly assign 1 slot to all other nodes, as shown in Figure 2. The $(s + i)$ values in Figure 2 are the time slots assigned to the nodes and the arrows show the direction of packets sent in time slot $(s + i)$. Each node then transmits its message to one of its neighbours on the path. In turn, the nodes on the path use 2 slots to send their aggregated values to the two sinks, one slot for each sink.

In the example, there are 5 nodes that have 2 slots. However, we can further reduce the number of nodes with 2 slots to 4 by assigning only one slot to the neighbor of either Δ_1 or Δ_2 on the shortest path. For example, in Figure 2, the node with the slot number $s + 4$ may not use its time slot $s + 5$ as it can simultaneously send its aggregated data to both its neighbors ((i) the sink and (ii) the node with slots $(s + 3,\ s + 6)$) in a single slot (i.e., $s + 4$). Thus, the minimum number of nodes with at least two slots that can connect two sinks is captured in the following result (Corollary 1):

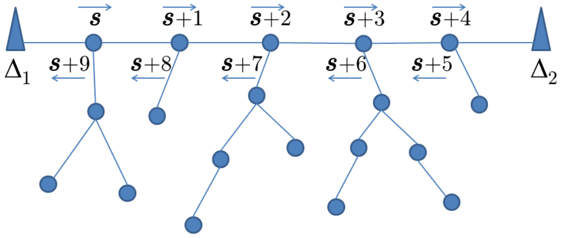


Figure 2: An example of network that solves weak DAS. Arrows show the sink to which the slot is related. s is an integer that shows the slot assigned to the node.

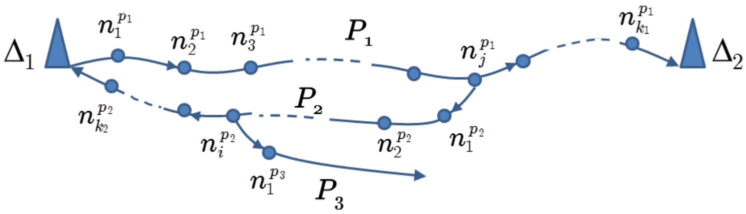


Figure 3: An illustration of the proof of Theorem 2.

Corollary 1. *Given a network* $G = (V, E)$ *with two sinks* Δ_1 *and* Δ_2*, then there exists a weak DAS* $\mathbb{S}$ *for* G*,* $\sum_{\forall n \in V} f_n^{\mathbb{S}} = l - 2$*, 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 $l-2$ 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. *Consider a finite network* $G = (V, E)$ *with two sinks* Δ_1 *and* Δ_2*, a path* $P = \Delta_1 \cdot n_1 \cdot n_2 \dots n_{l-1} \cdot \Delta_2$ *that is a shortest path between* Δ_1 *and* Δ_2 *of length* l *with* $l-1$ *nodes. Then, there exists no weak DAS schedule* $\mathbb{S}$ *for* G *such that* $\sum_{\forall n \in V} f_n^{\mathbb{S}} \leq l - 3$*.*

From Corollary 1, we know that it is possible to have a weak DAS schedule with at most $l-2$ nodes that assigned more than 2 slots. Now, we prove that it is impossible to have such a schedule with less than $l-2$ nodes.

Proof. We show that to have G with at most $l-3$ nodes that have at least 2 slots, G has to be infinite.

Let S_1 be a set of nodes that have already sent once (used 1 time slot) and S_2 be a set of nodes that have already sent at least twice (used 2 time slots), where $|S_1| \geq 0$ and $|S_2| \geq 0$. Let $P_1 = n_1^{p_1}, n_2^{p_1}, ..., n_{k_1}^{p_1}, \Delta_2$ be the path, of length $k_1 \geq l-1$, which delivers a packet of $n_1^{p_1}$ to Δ_2, where $n_1^{p_1}$ is a neighbour of Δ_1 and $\mathbb{S}(n_1^{p_1}) < \mathbb{S}(n_2^{p_1}) < ... < \mathbb{S}(n_{k_1}^{p_1})$. See Figure 3 for illustration. After delivering the packet of $n_1^{p_1}$ to Δ_2, the set S_2 becomes $S_2 = S_2 \cup (P_1 \cap S_1)$, i.e., some nodes on path P_1 could have sent one more time. Then,

(i) If $|S_2| \geq l-2$, then we are done.

(ii) Otherwise, $S_1 = S_1 \cup P_1$ and there exists a set of nodes on P_1 that sent only once. Let $n_j^{p_1}$ be the node on P_1 closest to Δ_2 that has sent only once. Note that now $|S_2| \geq k_1 - j$. As every node should send its packet to both Δ_1 and Δ_2, there exists a path $P_2 = n_j^{p_1}, n_1^{p_2}, n_2^{p_2}, ..., n_{k_2}^{p_2}, \Delta_1$, of length $k_2 + 1$, which delivers a packet of $n_j^{p_1}$ to Δ_1, where $\mathbb{S}(n_j^{p_1}) < \mathbb{S}(n_1^{p_2}) < \mathbb{S}(n_2^{p_2}) < ... < \mathbb{S}(n_{k_2}^{p_2})$. After delivering the packet of $n_j^{p_1}$ to Δ_1, if $|P_2 \cap S_1| = k_2$, i.e., all nodes on $P_2 \setminus n_j^{p_1}$ have already sent at least twice, then we are done, as $|S_2| \geq k_1 - j$ and $k_2 + k_1 - j \geq l - 2$. Otherwise, as in case(ii), the sets S_2 and S_1 become $S_2 = S_2 \cup (P_2 \cap S_1)$ and $S_1 = S_1 \cup P_2$. And there exists a set of nodes on P_2 that sent only once, $n_i^{p_2}$ on P_2 that sent only once and is the closest node to Δ_1, and P_3 that delivers a packet of $n_i^{p_2}$ to Δ_2. The step continues infinitely many times if G is infinite. However, as G is finite the step continues until there exists a path P_r such that $|S_2 \cup (P_r \cap S_1)| \geq l - 2$.

□

6. ALGORITHMS

Based on the results developed in Section 5, we develop a 3-stage weak DAS algorithm for WSNs with two sinks. 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 6.2. The final phase assigns slots to nodes in the network in such a way so as to satisfy a given property, e.g., minimum latency. This phase is explained in Section 6.3.

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 [2, 35, 18].

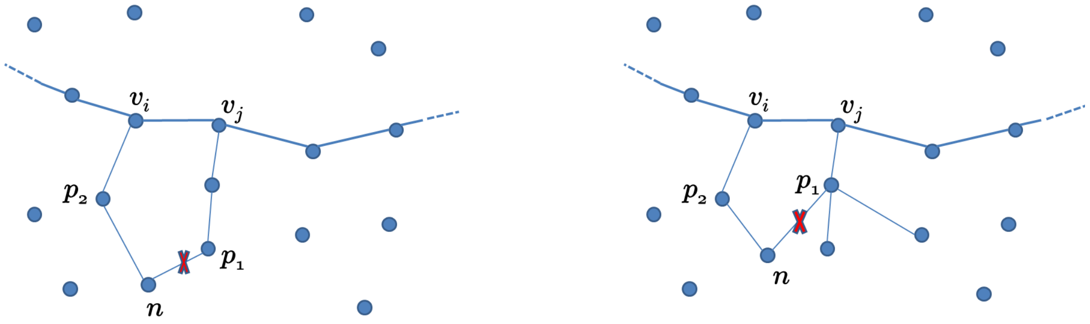
6.1. Phase 1: Computing the Shortest Path Between the two Sinks

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 $P = \Delta_1 \cdot n_1 \ldots n_l \cdot \Delta_2$ between Δ_1 and Δ_2.

After forming P, all nodes on P, apart from the two sinks, will take the role of *virtual sink* and set their variables to 1 and *hop* to 0. The reason the sinks are not virtual sinks is that they do not take part in data aggregation and forwarding. The second phase of the algorithm, which we describe in Section 6.2, then starts.

6.2. 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.



(a) Parent with smaller hop distance

(b) Parent with smaller number of children

Figure 4: Parent selection

The first two phases of our algorithm are somewhat similar to the algorithm proposed in [16], where authors propose an algorithm that forms a Greedy Incremental Tree (GIT)-like tree to perform energy-efficient in-network data aggregation. Their algorithm consists of first forming a shortest path between the first source node to a sink and then connecting all other source nodes to the path in a greedy fashion using hop number as a cost. The idea behind building GIT-like tree is that it improves path sharing, i.e., it allows earlier data aggregation to reduce data transmissions. However, their algorithm differs from ours in that their algorithm does not balance the number of children while our algorithm does. The next section explains our balancing algorithm.

6.2.1. Balanced tree formation

In this section, we describe the balanced tree formation (BTF) algorithm that we adopt (See Figure 7). When developing the balanced tree, we focus on two main parameters, in the following order: (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.

In other words, a node n will select node p_2 over its current parent p_1 only if

- p_2 has a smaller hop distance (from a virtual sink) than that of p_1. Figure 4(a) illustrates this case.
- 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. Figure 4(b) illustrates this case.

A node can be in one of five states: ALONE, TEMP, JOINED, BALANCED and SCHEDULE. 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 BALANCED state when it finds a potential parent with a smaller number of children. In the TEMP or BALANCED state, a node waits for some time to get a response from the potential parent.

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 the hop distance of its parent hop with the hop distance 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.

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 7:*

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

1. $(m.parent \neq \bot \Rightarrow m.hop \neq \infty)$
2. $(m.hop \leq m.hop')$
3. $[(m.parent' \neq m.parent) \Rightarrow ((m.hop < m.hop') \vee ((m.hop = m.hop') \wedge (m.parent.numchild < m.parent'.numchild')))]$

The conditions mean the following: (i) The first states that if *parent* is set (i.e, not undefined), then *hop* is set too, (ii) *hop* cannot increase during execution and (iii) if *parent* changes, then either *hop* value decreases or the node is joining a parent with a smaller number of children.

Proof. To prove that the above is an invariant, we show that it is satisfied in the initial state of the program and subsequent action preserves the invariant (Note that the primed variable indicates the value from the previous state).

The invariant is trivially satisfied in the initial state where $parent = \bot$ and $hop = \infty$. In state ALONE, the invariant is not violated as no state change occurs. In state TEMP, the value of hop decreases since a node m receives $\langle ACCEPT \rangle$ from a node n only if n has a smaller hop (line 2 state ALONE, and line 12 state JOINED), which preserves the invariant. In state TEMP, the value of the parent changes too as either m gets a new parent with a smaller hop (line 12 state JOINED) or gets a parent for the first time (line 2 state ALONE), which preserves the invariant. In state BALANCED, when node m receives a $\langle BAL\_ACCEPT \rangle$ message, m changes parent due to m having a possible new parent with fewer children (state JOINED line 15). In state JOINED, when node m receives a $\langle JOIN \rangle$ packet, it updates its state based on that of its parent's, which preserves the invariant. ☐

6.3. 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*.

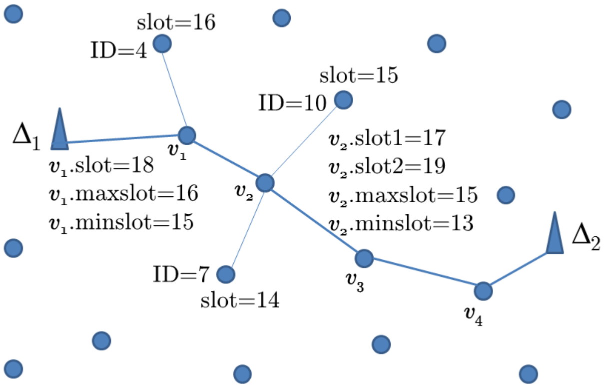


Figure 5: Scheduling example. The network has 20 nodes. v_2 is the parent of the nodes with ID=10 and ID=7. v_1 is the parent of the node with ID=4.

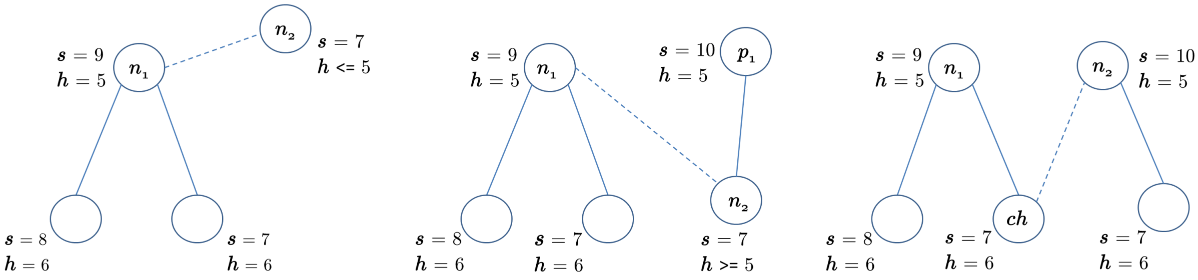
6.3.1. *Energy-Efficient Collision Free (EECF) DAS Algorithm for Balanced Tree*

In this section, we propose a DAS algorithm that leverages the balanced tree obtained (see Section 6.2.1). 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 [2, 35, 18]. This energy saving comes in addition to that obtained from duty cycling. Further, since the tree is balanced (at a given level), then nodes at that level spend comparable amount of energy, without creating energy holes in the network (assuming similar sensing loads).

We propose a weak DAS algorithm that works in a greedy fashion (see Figure 8). In the algorithm, every node maintains variables *maxslot* and *minslot*. These variables are used by a node to inform its neighbours 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 Δ_1, without loss of generality. As we have proved, there should exist at least $l - 2$ nodes with at least two slots. Thus, all virtual sinks 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 compute their ranks themselves.

Example. For the sake of clarity, consider the example in Figure 5, where the number of nodes is 20, including



(a) Node n_2 has a smaller or equal hop distance to n_1's hop distance

(b) Node n_2's parent's slot is bigger than n_1's slot

(c) Node n_1's child *ch* shares the same slot with a child of n_2 that has bigger slot than n_1's slot.

Figure 6: Different scheduling cases, where s denotes slot number and h the hop number. A solid line between nodes show the parent-child relationship, a dotted line shows the existence of a communication link between nodes.

2 sinks and 4 virtual sinks. According to the algorithm, the only slot of v_1 will be 18, i.e., v_1.slot=18. The first and second slots of v_2, v_3 and v_4 will be {17, 19}, {16, 20} and {15, 21} respectively, e.g., v_2.slot1=17 and v_2.slot2=19. The *maxslot* of v_1 will be 2 less than its slot, that is 16. And, as v_1 has only one child, the *minslot* will be $16-1 = 15$. The *maxslot* of v_2 will be $17 - 2 = 15$ and *minslot* will be $15 - 2 = 13$. The children of v_2 with IDs 10 and 7 will take their slots from the range (*maxslot*, *minslot*+1), i.e., (15, 14), according to their ranks. In this case, the slot of node with ID=10 will take slot 15, and the node with ID=7 will take slot 14.

If a node detects a slot conflict, the node then decides whether to change the slots of its children, depending on the *priority* attributes, namely the hop distance, slot and rank in that order. This change of schedule whenever a collision is detected will eventually ensure that the schedule is collision-free. The possible changes are illustrated in Figure 6. A node n_1 tells its children to change their slots if

- n_1 finds a neighboring node n_2 that shares the same slot with its child and n_2 has a smaller or equal hop distance to n_1's hop distance (lines 20-30 of Figure 7, 8). Figure 6(a) illustrates this case.
- n_1 finds a neighboring node n_2 that shares the same slot with its child and n_2's parent slot is bigger than n_1's slot (lines 37-43 of Figure 8). Figure 6(b) illustrates this case.
- one of n_1's child *ch* is asked to change because *ch* shares 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 (lines 16-19, 31-35 of Figure 7, 8). Figure 6(c) illustrates this case.

After all the nodes have been assigned their slots, all nodes send their slot values to Δ_1, which computes the minimum of the slots values. It then broadcasts that value to the nodes for correction. The nodes, after receiving the minimum value, can compute their final slots by taking the difference of their current slot and the minimum value, and adding 1. Since the schedule was collision-free and all nodes deduct the same minimum value from their slot value, the schedule remains collision-free. 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:*

$\forall m \in V ::$

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

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

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

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

Proof. $I0, I1$ follow trivially from the program (statements 2-7). $I2$ is satisfied by statements on lines $8-13$ (which ensures that $m.slot < m.parent.slot$) and $20-40$, in case of slot collisions. $I3$ is handled through any case from statements $20-40$ to resolve slot collisions. □

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. $A; B$ means that A executes first and B starts once A has terminated.*

Proof. Follows directly from Lemmas 1 and 2. □

7. Experimental Setup

In this section, we describe (i) the simulation setup we use to evaluate the performance of EECF-DAS and (ii) the testbed we use to deploy EECF-DAS to ensure that the protocol works on real hardware.

7.1. TOSSIM Simulation Experiment Setup

We have performed TOSSIM [26] simulations to evaluate the performance of EECF-DAS algorithm in a stand-alone fashion. We have evaluated it on networks of sizes 400, 600, 800 and 1000 nodes. We constructed the networks such that a node has a communication radius of 10 m, 15 m and 20 m, and a node hears another node in the communication range at -65 dBm [40]. Each node is given a noise model from the "casino-lab" noise trace file, which is taken in the Casino Lab of Colorado School of Mines. The nodes were uniformly distributed on a 100 m×100 m surface. We placed the two sinks i) in two diagonally opposite corners and ii) randomly such that the distance between them is between 3 and 8 hops.

7.2. Indriya Testbed Experiment Setup

To confirm the consistency of simulation results, we also ran EECF-DAS algorithm on the Indriya testbed [8], which has 3D topology and has been deployed over three floors of the School of Computing building of the National University of Singapore. The Indriya testbed allows registered users to run and test protocols remotely by having them upload their programs and download data dumped from the program to the USB port. When we performed

```
Process $i$

Variables of $i$
$state$ ∈{ALONE, TEMP, JOINED, BALANCED, 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=BALANCED
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. 8
   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=$hop$ ∧ $parent.numchild$-$n\_numchild$≥2)
    $state$:=BALANCED
    send($REQ\_BAL, i, n, parent$)
  endif
upon rcv$\langle REQ, n, i \rangle$
   send($ACCEPT, i, n, hop, |children|$)
   $children$:=$children$ ∪{$n$}
   $j := 0$
upon rcv$\langle REQ\_BAL, n, i, n\_parent \rangle$
   if($n\_parent.numchild - |children|$ ≥2)
     $children$:=$children$ ∪{$n$}
     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 7: Balanced tree formation algorithm

```
**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 7)
**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**$((\alpha.parentslot{>}slot \vee (\alpha.parentslot{=}slot \wedge \alpha.id{>}i))$
39           $\wedge(\alpha.slot \leq maxslot \wedge \alpha.slot > minslot))$
40     $maxslot := \alpha.slot - 1$
41     $minslot := maxslot - |children|$
42     **broadcast**$(SLOT, threshS)$
43   **endif**
44 **endif**

% broadcasts the SLOT packet x times
**broadcast**$(SLOT, x)$
1  $s := 0$
2  **while**$(s < x)$
3    **bCast**$(SLOT, \alpha : P)$
4    $s := s + 1$
```

Figure 8: Data aggregation scheduling algorithm

Constant	**Value**
threshJ	15
threshS	10

Table 1: Parameter values

the experiments, the number of nodes in Indriya was about 100. The nodes, which are powered over USB, are TelosB motes with CC2420 radio, 8 MHz CPU, 10 KB RAM and 48 KB of program memory. We selected the node with ID = 1 as sink Δ_1 and node ID = 46 as sink Δ_2. The transmission power level of the nodes can be set to different levels from 3 (-25 dBm) up to 31 (0 dBm). To increase the diameter (largest hop number) of the network, we set the transmission power level to 7 [4]. The number of hops between sink Δ_1 and sink Δ_2 is then 5.

7.3. Cluster-Based DAS Scheduling (CDAS)

A cluster-based DAS scheduling algorithm has been proposed in [46], against which we compare our algorithm. The authors, in order 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 cluster-based algorithm adopts the CDS construction algorithm proposed in [43] which, in turn, is based on a variant of a solution to the Maximal Independent Set problem. 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 of the algorithm, we refer the reader to [46].

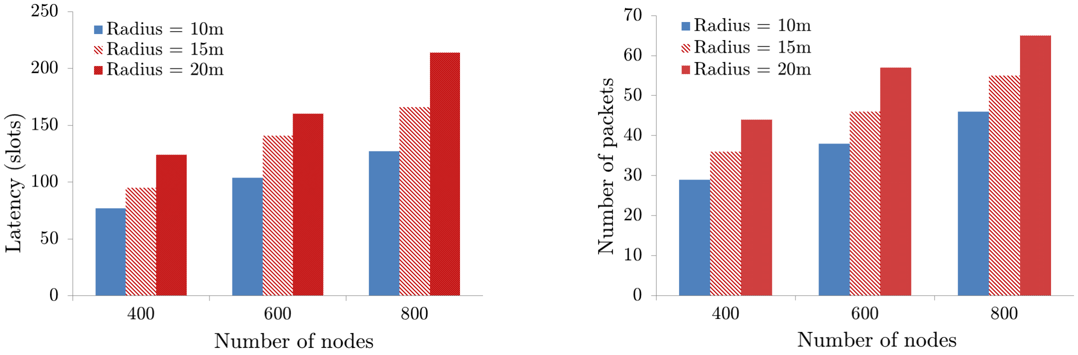
7.4. High Level Simulation in Java

Apart from evaluating the performance of EECF-DAS, we also wish to compare it against other protocols. However, to compare the performance of EECF-DAS against another protocol is challenging due to the dearth of TDMA-based protocol for DAS scheduling with two sinks. Thus, we adapt CDAS (explained in Section 7.3) to work in a WSN with two sinks, in two ways: (i) we ran CDAS 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 [43], we selected each virtual sink (a node on the shortest path except the sinks) as a root of a dominating tree and we called this adapted algorithm SP-DAS.

Also, as CDAS was only implemented at a high level (in C++) in [46], rather than using a standard simulator such as TOSSIM, we developed a high-level implementation of EECF-DAS in Java and we also then implemented CDAS in Java, for comparison purposes.

7.5. Algorithm and Experimental Parameters

The constant values used in the algorithm are given in Table 1. The values are used to send corresponding packets more than once as there could be packet losses, though it does not solve the packet losses problem completely. The values could affect the total number of transmitted packets to complete the scheduling.



(a) The average latency over 10 runs. (b) The number of packet transmissions per node.

Figure 9: The average latency and number of packet transmissions with different network sizes (EECF)

7.6. Metrics

We compared (i) the latency of the generated schedule, which is equal to the largest slot of the nodes in the network, and (ii) the number of slots each node should be awake to transmit and receive, i.e., we focus on the profile of the schedule in terms of "contiguousness" of the schedule.

8. RESULTS

We now present the simulation and testbed results to show the correctness and performance of EECF-DAS.

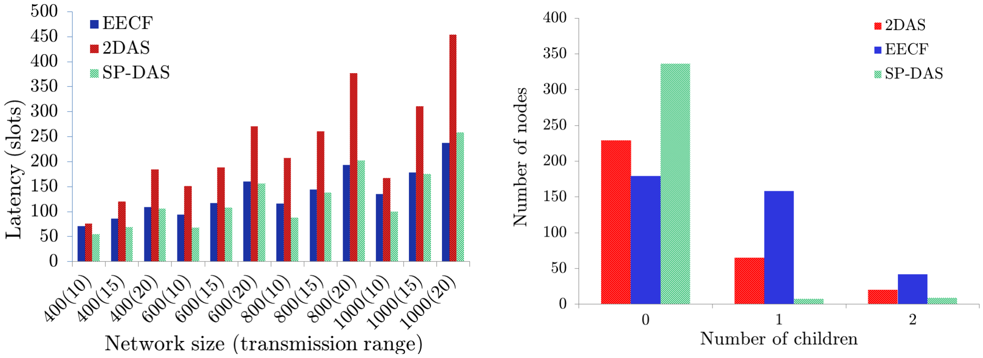
8.1. TOSSIM Simulations

We show the performance profile of EECF-DAS and compare it against SP-DAS and 2DAS.

8.1.1. Performance Evaluation of EECF-DAS

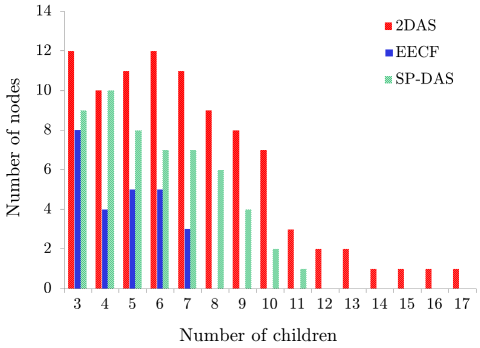
Latency: Figure 9 shows the latency and the number of packets transmitted to complete the scheduling when simulated with TOSSIM. The average latency is shown in Figure 9(a). It can be observed that the latency is low compared to the network size, although EECF considers contiguous slots only. Also we see that the latency is directly related to the neighborhood size/network density. We believe this to be the case since it becomes more difficult to find free contiguous slots with increasing neighbourhood size. Thus, to obtain such slots, the schedule needs to be extended, resulting in larger latency.

Messages Complexity: Figure 9(b) shows the average number of packet transmissions per node to complete the slot assignment. It can be observed that the number of messages increases linearly as the network size increases (or neighborhood size/network density increases). This is intuitive as each node needs to communicate to be assigned a slot. This further shows EECF-DAS has linear message complexity and will scale with networks of bigger size. Further, the results may show that several packets need to be exchanged per node to complete the scheduling. This is not a weakness of the algorithm as the reason behind the perceived high number of packets is our attempt to compensate for packet losses. As we do not specifically address faulty situations, we perform retransmissions



(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 10: Comparison of EECF, SP-DAS and 2DAS

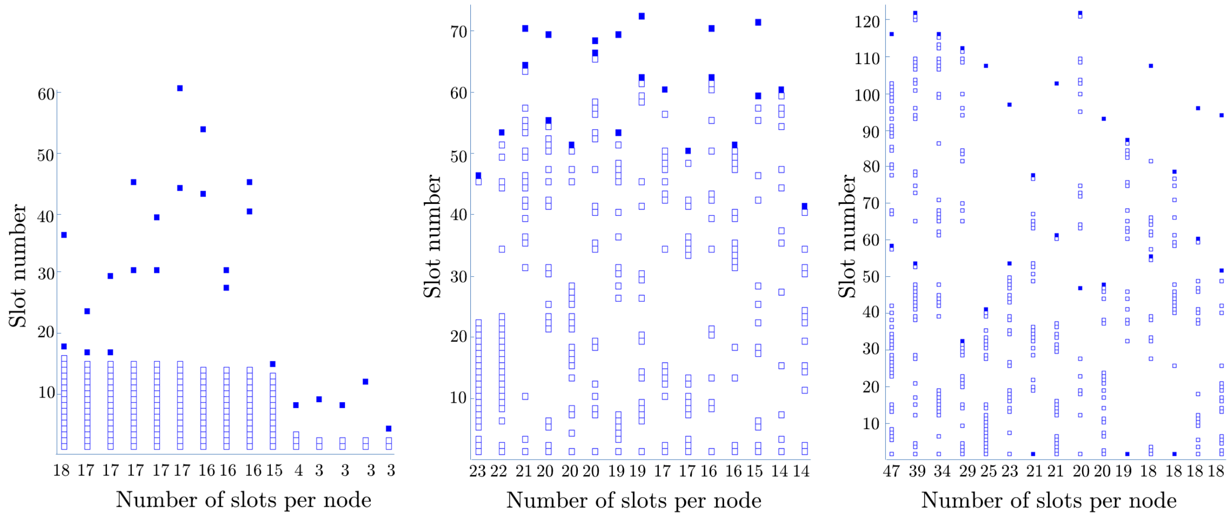
regardless of message deliveries. This can be easily remedied through the use of acknowledgements, which will drastically reduce the number of packets used.

8.2. High Level Simulations for Comparison of EECF-DAS, 2DAS and SP-DAS With Diagonal Sink Positions

In this section, we look at the performance of the various protocols under study, when the sinks are placed diagonally opposite each other.

8.2.1. Latency and Message Complexity

Figure 10 shows the latency and the number of children obtained for the three algorithms, namely EECF-DAS, 2DAS and SPDAS, executed on a network where the two sinks were placed at opposite corners of the network. Figure 10(a) shows the number of slots required for a DAS schedule for networks of different sizes and different transmission ranges. It can observed from Figure 10 that, in some cases, the latency of EECF and SP-DAS can be up to 50% smaller than that of 2DAS. This shows the advantage of using a backbone for slot assignment in WSNs with more than one sink. It can also be noticed that SP-DAS shows slightly better results in networks where nodes have smaller transmission range. However, as the transmission range gets bigger, EECF performs better than SP-DAS. This is because, as the transmission range gets bigger, the number of clusters built by SP-DAS gets smaller, and SP-DAS cannot benefit much from the spatial advantage (see Section 7.3).



(a) The number of slots per node (EECF) (b) The number of slots per node (SP-DAS) (c) The number of slots per node (2DAS)

Figure 11: Comparison of EECF, SP-DAS and 2DAS (400 nodes, transmission range=15m)

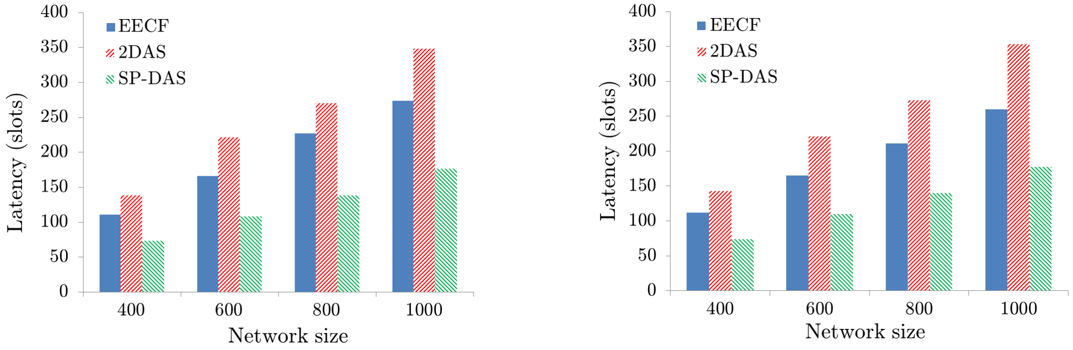
8.2.2. Balanced Tree Property

Figures 10(b) and 10(c) show the distribution of the number of children the various nodes in networks constructed by EECF, SP-DAS and 2DAS have. As can be observed, 2DAS generates more nodes with a large number of children, which implies that nodes in 2DAS would typically be expected to stay awake longer than in EECF and in SP-DAS, thereby consuming more energy. Further, the effect of using a balancing algorithm as EECF, as opposed to SP-DAS, can be observed in Figures 10(b) and 10(c). As the nodes were uniformly distributed, a high proportion of the nodes have at most two children. On the other hand, we observe that the nodes that are on the shortest path, i.e., the virtual sinks, have a higher number of children. This is due to the fact that each of the one-hop neighbours of the virtual sinks connects to one virtual sink. Specifically, in our BTF algorithm, a node first chooses a parent based on its hop distance (see Section 6.2.1). Overall, from Figure 10, we conclude that algorithms that use the shortest path as a backbone (i.e., EECF and SP-DAS) show better results in terms of latency while EECF-DAS builds a more balanced tree.

8.2.3. Schedule Profile

Figure 11 shows the transmission and reception time slots, i.e., the schedule profile, of the 15 nodes of each of EECF, SP-DAS and 2DAS that have to wait for the maximum number of slots before completing transmission, in a network of 400 nodes with nodes having a transmission range equal to 15 m and where two sinks were placed at opposite corners of the network. The filled rectangles indicate the transmission slots whereas the empty ones indicate reception slots of one of the selected nodes. We make the following important observations:

1. The slot assignment under EECF is contiguous, i.e., a node has to receive messages from its children for a number of consecutive slots before it can transmit an aggregated message (where a filled rectangle appears at the end of the sequence). On the other hand, the reception slots of SP-DAS and 2DAS are usually separated.



(a) Distance between two sinks is 4 hops.

(b) Distance between two sinks is 6 hops.

Figure 12: Comparison of EECF, SP-DAS and 2DAS (transmission range=15m) with randomly placed sinks

2. Under EECF, the nodes need to 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. The maximum number of switches is 20 and 13 respectively. We can thus infer that, by balancing trees and assigning contiguous slots to children, one can increase the sleeping time of nodes and reduce the number of sleep-active transitions, thereby reducing the energy consumption of nodes.

Another observation is that, since both EECF and SP-DAS use a shortest path in their aggregation tree, the number of nodes with 2 transmission slots should be equal. However, in Figure 11(a), we can see that there are 9 nodes in EECF and only 7 nodes in SP-DAS with 2 transmission slots. This is because only the nodes with the maximum number of slots (15 in all) is shown in Figure 11 and, in SP-DAS, there can be nodes that have more children than the nodes on the shortest path, i.e., the virtual sinks.

8.3. High Level Simulations for Performance Comparison of EECF-DAS, 2DAS and SP-DAS With Randomly Placed Sinks

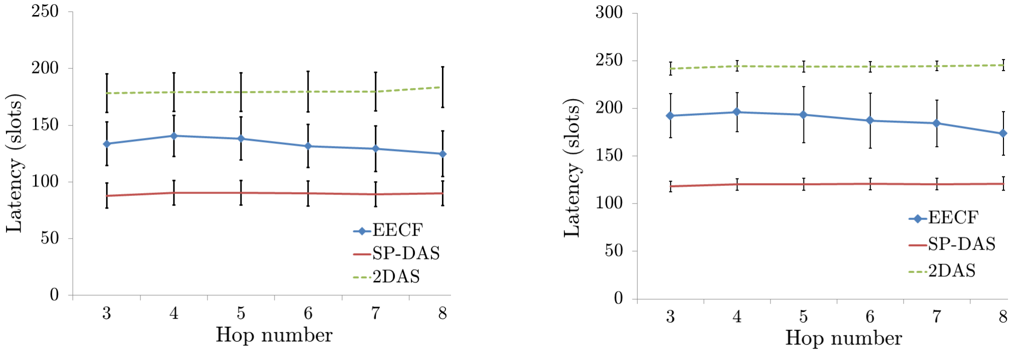
In this section, we study the possible impact of randomly placed sinks on the various protocols under study.

8.3.1. Latency

Figures 12(a) and 12(b) show the latency obtained from EECF, SP-DAS and 2DAS running on networks with varying number of nodes, where the two sinks were placed randomly such that the distance between them is 4 and 6 hops. From these two figures and from Figure 13, we observe that the distance between the two sinks does not seem to affect the latency. On the other hand, we observe the impact of the network size on the latency. Figure 13 also shows, as previously observed with fixed sinks, that EECF performs better when the distance between the two sinks increases.

8.3.2. Schedule Profile

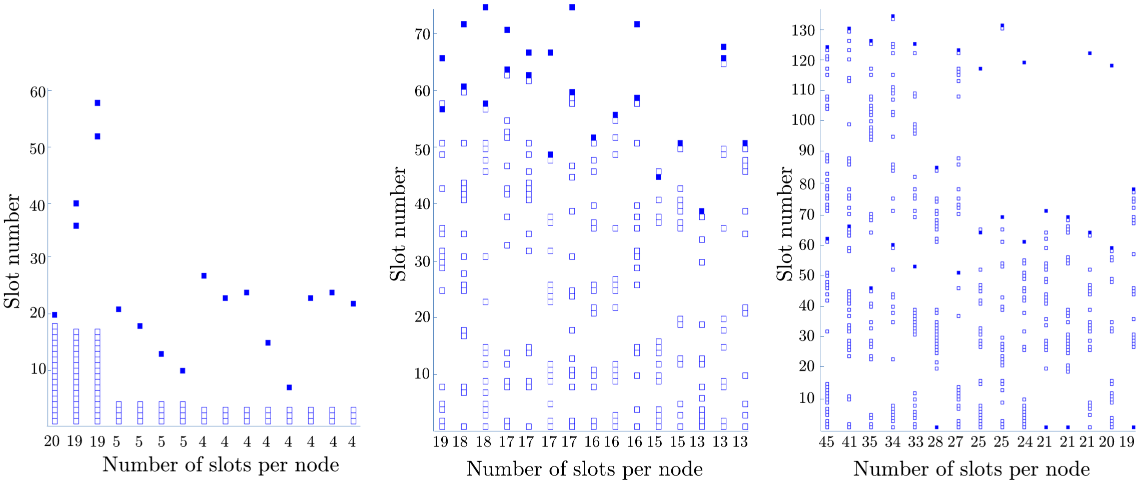
Figure 15 shows the transmission and reception time slots of the 15 nodes of EECF, SP-DAS and 2DAS that wait the maximum number of slots before transmission, in a network of 400 nodes with a transmission range equal



(a) Number of nodes = 500

(b) number of nodes = 700

Figure 13: Comparison of EECF, SP-DAS and 2DAS, transmission range=15m



(a) EECF.

(b) SP-DAS.

(c) 2DAS.

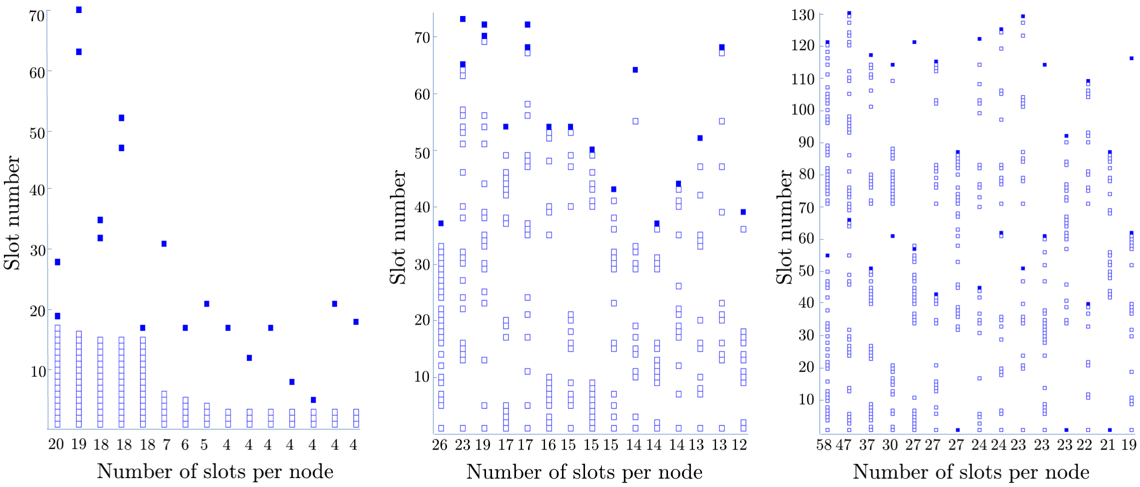
Figure 14: Distribution of slots of 15 nodes that have maximum number of slots of EECF, SP-DAS and 2DAS (400 nodes, transmission range = 15m, distance between 2 sinks = 4 hops)

to 15m. The distance between the two sinks is set to 4 and 6 hops. From the figure, we again observe that (i) slots in EECF are contiguous and (ii) the number of nodes with a large number of receive slots (children) is roughly the number of hops between two sinks, i.e., the number of nodes with highest number of slots match the lower bound of $l-2$ identified earlier.

8.3.3. Sleep-Active Transitions

Figure 16 shows the number of sleep-active transitions of EECF, SP-DAS and 2DAS in networks with 500 and 700 nodes with varying distances between the two sinks. The number of sleep-active transitions in EECF is always 3 whereas in SP-DAS and 2DAS increases as the network size increases.

Figures 15 and 16 corroborate the fact that nodes in EECF can reduce energy cost due to reduced number of sleep-active transition, which is independent of the distance between the two sinks, and the total up time.

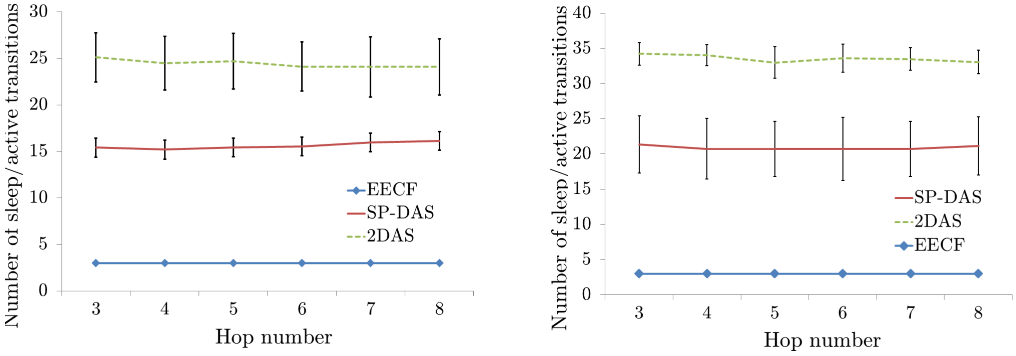


(a) EECF.

(b) SP-DAS.

(c) 2DAS.

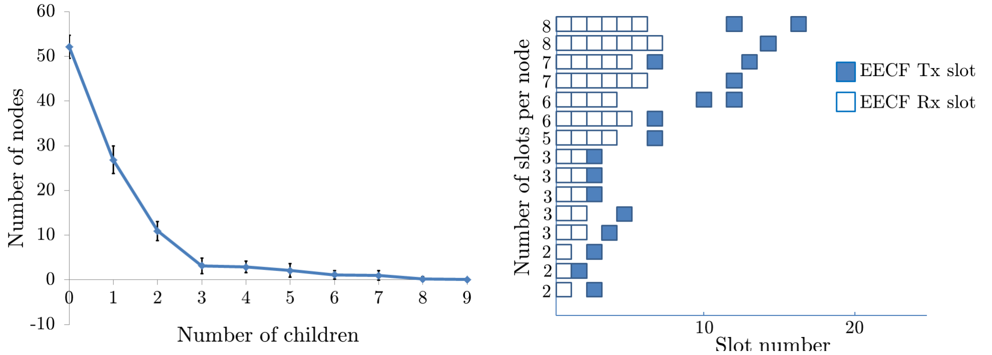
Figure 15: Distribution of slots of 15 nodes that have maximum number of slots of EECF, SP-DAS and 2DAS (400 nodes, transmission range = 15m, distance between 2 sinks = 6 hops)



(a) Number of nodes = 500

(b) Number of nodes = 700

Figure 16: Comparison of EECF, SP-DAS and 2DAS, transmission range=15m



(a) Number of children per node.

(b) Distribution of slots of 15 nodes that have maximum number of slots of EECF.

Figure 17: Indriya Testbed results

8.4. Indriya Testbed Results

To confirm the correctness of our algorithms in a real-world environment, we also performed testbed experiments. Figure 17 shows the results obtained from running EECF-DAS on Indriya. Figure 17(a) shows the the children distribution obtained from EECF-DAS algorithm. As can be observed, most of the nodes (about 90%) have at most 2 children, with the virtual sinks having between 3 and 7 children. This shows that, by balancing the number of children, the number of nodes with a large number of children can be reduced, implying that most of the nodes will wake up for short periods of time only. The result also corroborates simulation results.

Figure 17(b) shows the transmission and reception time slots of the 15 nodes of EECF with the maximum number of slots before final transmission. The filled slots indicate the transmission slots and empty slots indicate reception slots. We observe that the resulting schedule when executing EECF on Indriya matches that obtained during simulations. Further, as during simulations, EECF assigned contiguous slots to nodes, reducing the number of sleep-active transition, which can reduce the energy cost.

9. CONCLUSION

In this paper, we have addressed the problem of data aggregation scheduling (DAS) in WSNs with two sinks. Before presenting our algorithm, we have formalized the DAS problem for two sinks. Then, we have showed that it is impossible to have a schedule in which all nodes have only one slot. Consequently, we have obtained a lower bound on the number of nodes required to have multiple slots. Based on the theoretical results, we have proposed an emery-efficient DAS algorithm that (i) balances the number of children at various levels, and (ii) allocates contiguous slots to siblings. We performed both simulation and real-world testbed experiments to evaluate the performance of our algorithm. The experimental results show that our algorithm works as expected and generates schedules with low latency, compared to an algorithm that have been developed for a WSN with a single sink.

One issue that arose during the work was whether the proposed algorithm is applicable to standardised TSCH-based networks (IEEE 802.15.4-2015). Channel contention is one of the main factors that causes increased energy usage in WSNs, which can be caused by co-located wireless systems using the same spectral space. Time slotted technique is one approach to reduce channel contention, however it cannot handle problems such as co-located wireless systems. On the other hand, channel hopping enables periodic changes in the operating frequency and the technique has been adopted in the form of time slotted channel hopping (TSCH) by IEEE 802.15.4e standard. The algorithm proposed in this paper will work with TSCH-based networks, with the benefit being that the latency can be further reduced by getting neighbouring nodes to transmit on different frequencies.

10. REFERENCES

[1] Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., Cayirci, E., 2002. Wireless sensor networks: a survey. Computer Networks 38 (4), 393–422.

[2] Akyildiz, I. F., Vuran, M. C., 2010. Wireless Sensor Networks. John Wiley and Sons, Ltd.

[3] Bo, Y., Li, J., 2011. Minimum-time aggregation scheduling in multi-sink sensor networks. In: SECON. IEEE, pp. 422–430.

[4] CC2420: 2.4 GHz IEEE 802.15.4/ZigBee RF Transceiver, . http://www.ti.com/lit/gpn/cc2420.

[5] Das, A., Dutta, D., Jul. 2005. Data acquisition in multiple-sink sensor networks. SIGMOBILE Mob. Comput. Commun. Rev. 9 (3), 82–85.

[6] Deng, R., He, S., Chen, J., 2016. Near-optimal online algorithm for data collection by multiple sinks in wireless sensor networks. IEEE Transactions on Control of Network Systems (99).

[7] Dijkstra, E. W., 1974. Self-stabilizing systems in spite of distributed control. Commun. ACM 17 (11), 643–644.

[8] Doddavenkatappa, M., Chan, M. C., Ananda, A. L., 2011. Indriya: A low-cost, 3d wireless sensor network testbed. In: TRIDENTCOM. Vol. 90. Springer, pp. 302–316.

[9] Dolev, S., 2000. Self-Stabilization. MIT Press.

[10] El-Fouly, F. H., Ramadan, R. A., Mahmoud, M. I., Dessouky, M. I., 2016. Rebtam: reliable energy balance traffic aware data reporting algorithm for object tracking in multi-sink wireless sensor networks. Wireless Networks, 1–19.

[11] Gilbert, E. N., Pollak, H. O., 1968. Steiner minimal tree. SIAM Journal on Applied Mathematics 16, 1–29'.

[12] Gnawali, O., Fonseca, R., Jamieson, K., Kazandjieva, M., Moss, D., Levis, P., Dec. 2013. Ctp: An efficient, robust, and reliable collection tree protocol for wireless sensor networks. ACM Trans. Sen. Netw. 10 (1), 1–49.

[13] Hamid, A., Ehsan, S., Hamdaoui, B., Aug 2014. Rate-constrained data aggregation in power-limited multi-sink wireless sensor networks. In: 2014 International Wireless Communications and Mobile Computing Conference (IWCMC). pp. 500–504.

[14] Heinzelman, W. B., Chandrakasan, A. P., Balakrishnan, H., Oct 2002. An application-specific protocol architecture for wireless microsensor networks. IEEE Transactions on Wireless Communications 1 (4), 660–670.

[15] Hill, J., et al., 2000. System architecture directions for networked sensors. In: Proceedings of the 9^{th} International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS).

[16] Intanagonwiwat, C., Estrin, D., Govindan, R., Heidemann, J., July 2002. Impact of network density on data aggregation in wireless sensor networks. In: In Proceedings of International Conference on Distributed Computing Systems (ICDCS). Vienna, Austria.

[17] Jhumka, A., 2010. Crash-tolerant collision-free data aggregation scheduling for wireless sensor networks. In: SRDS 2010. pp. 44–53.

[18] Jolly, G., Younis, M., May 2005. An energy-efficient, scalable and collision-free mac layer protocol for wireless sensor networks. Wirel. Commun. Mob. Comput. 5 (3), 285–304.

[19] K. Vaidhyanathan, S. Sur, S. N. P. S., 2004. Data aggregation techniques sensor networks. Tech. Rep. Technical Report, OSU-CISRC-11/04-TR60, Ohio State University.

[20] Karp, R. M., 1972. Reducibility among combinatorial problems. In: Proceedings of a symposium on the Complexity of Computer Computations. pp. 85–103.

[21] Kawano, R., Miyazaki, T., 2008. Distributed data aggregation in multi-sink sensor networks using a graph coloring algorithm. AINA, 934–940.

[22] Krishnamachari, B., Estrin, D., Wicker, S. B., 2002. The impact of data aggregation in wireless sensor networks. In: Proceedings of the 22nd International Conference on Distributed Computing Systems. pp. 575–578.

[23] Kuo, T. W., Lin, K. C. J., Tsai, M. J., Oct 2016. On the construction of data aggregation tree with minimum energy cost in wireless sensor networks: Np-completeness and approximation algorithms. IEEE Transactions on Computers 65 (10), 3109–3121.

[24] Leao, L., Felea, V., Guyennet, H., Nov 2016. MAC-aware routing in multi-sink wsn with dynamic back-off time and buffer constraint. In: 8th IFIP International Conference on New Technologies, Mobility and Security.

[25] Lee, H., Klappenecker, A., Lee, K., Lin, L., 2005. Energy efficient data management for wireless sensor networks with data sink failure. IEEE MASS 0, 203–210.

[26] Levis, P., Lee, N., Welsh, M., Culler, D., 2003. Tossim: accurate and scalable simulation of entire tinyos applications. In: SenSys '03. pp. 126–137.

[27] Lindsey, S., Raghavendra, C., Sivalingam, K. M., Sep. 2002. Data gathering algorithms in sensor networks using energy metrics. IEEE Trans. Parallel Distrib. Syst. 13 (9), 924–935.

[28] Mottola, L., Picco, G. P., 2011. Muster: Adaptive energy-aware multisink routing in wireless sensor networks. IEEE Trans. Mob. Comput. 10 (12), 1694–1709.

[29] Murugan, K., Pathan, A.-S. K., Jun 2016. Prolonging the lifetime of wireless sensor networks using secondary sink nodes. Telecommun. Syst. 62 (2), 347–361.

[30] Rajagopalan, R., Varshney, P. K., Oct. 2006. Data-aggregation techniques in sensor networks: A survey. Commun. Surveys Tuts. 8 (4), 48–63.

[31] Rajendran, V., Garcia-Luna-Aveces, J., Obraczka, K., Nov 2005. Energy-efficient, application-aware medium access for sensor networks. In: Mobile Adhoc and Sensor Systems Conference, 2005. pp. 623–630.

[32] Rajendran, V., Obraczka, K., Garcia-Luna-Aceves, J. J., Feb. 2006. Energy-efficient, collision-free medium access control for wireless sensor networks. Wirel. Netw. 12 (1), 63–78.

[33] Saginbekov, S., Jhumka, A., Shakenov, C., 2016. Towards energy-efficient collision-free data aggregation scheduling in wireless sensor networks with multiple sinks. In: SENSORNETS 2016 - Proceedings of the 5th International Confererence on Sensor Networks. pp. 77–86.

[34] Shan, M., Chen, G., Luo, D., Zhu, X., Wu, X., Jul. 2014. Building maximum lifetime shortest path data aggregation trees in wireless sensor networks. ACM Trans. Sen. Netw. 11 (1), 1–24.

[35] Shih, E., Calhoun, B., Cho, S., Chandrakasan, A., 2001. Energy-efficient link layer for wireless microsensor networks. In: VLSI, 2001. Proceedings. IEEE Computer Society Workshop on. pp. 16–21.

[36] Sitanayah, L., Brown, K. N., Sreenan., C. J., 2012. Multiple sink and relay placement in wireless sensor networks. In: WAITS 2012. pp. 18–23.

[37] Sohrabi, K., Gao, J., Ailawadhi, V., Pottie, G., Oct 2000. Protocols for self-organization of a wireless sensor network. Personal Communications, IEEE 7 (5), 16–27.

[38] Tan, H. O., Körpeoğlu, I., Dec. 2003. Power efficient data gathering and aggregation in wireless sensor networks. SIGMOD Rec. 32 (4), 66–71.

[39] Thulasiraman, P., Ramasubramanian, S., Krunz, M., 2007. Disjoint multipath routing to two distinct drains in a multi-drain sensor network. In: INFOCOM. IEEE, pp. 643–651.

[40] Tossim: Configuring a Network, http://tinyos.stanford.edu/tinyos-wiki/index.php/TOSSIM, .

[41] Tuysuz Erman, A., Havinga, P., 2010. Data dissemination of emergency messages in mobile multi-sink wireless sensor networks. In: Med-Hoc-Net 2010. pp. 1–8.

[42] Valero, M., Xu, M., Mancuso, N., Song, W.-Z., Beyah, R. A., 2012. Edr^2: A sink failure resilient approach for wsns. In: ICC 2012. IEEE, pp. 616–621.

[43] Wan, P.-J., Alzoubi, K. M., Frieder, O., 2004. Distributed construction of connected dominating set in wireless ad hoc networks. Mobile Network Applications 9 (2), 141–149.

[44] Ye, W., Heidemann, J., Estrin, D., 2002. An energy-efficient mac protocol for wireless sensor networks. In: INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE. Vol. 3. pp. 1567–1576.

[45] Younis, O., Fahmy, S., Oct 2004. Heed: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. IEEE Transactions on Mobile Computing 3 (4), 366–379.

[46] Yu, B., Li, J., Li, Y., 2009. Distributed data aggregation scheduling in wireless sensor networks. In: 28th IEEE International Conference on Computer Communications, Joint Conference of the IEEE Computer and Communications Societies, 19-25 April 2009, Rio de Janeiro, Brazil, INFOCOM. pp. 2159–2167.

[47] Zhao, C., Zhang, W., Yang, X., Yang, Y., Song, Y. Q., June 2014. A novel compressive sensing based data aggregation scheme for wireless sensor networks. In: IEEE Int. Conference on Communications. pp. 18–23.

[48] Zhou, H., Qing, D., Zhang, X., Yuan, H., Xu, C., 2012. A multiple-dimensional tree routing protocol for multisink wireless sensor networks based on ant colony optimization 8.