Tree-Based Wireless Sensor Networks in Fast Data Collection

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Abstract:

We investigate the following fundamental question - how fast can information be collected from a wireless sensor network organized as tree? To address this, we explore and evaluate a number of different techniques using realistic simulation models under the many-to-one communication paradigm known as converge cast. We first consider time scheduling on a single frequency channel with the aim of minimizing the number of time slots required (schedule length) to complete a converge cast. Next, we combine scheduling with transmission power control to mitigate the effects of interference, and show that while power control helps in reducing the schedule length under a single frequency, scheduling transmissions using multiple frequencies is more efficient. We give lower bounds on the schedule length when interference is completely eliminated, and propose algorithms that achieve these bounds. We also evaluate the performance of various channel assignment methods and find empirically that for moderate size networks of about 100 nodes, the use of multi-frequency scheduling can suffice to eliminate most of the interference. Then, the data collection rate no longer remains limited by interference but by the topology of the routing tree. To this end, we construct degree-constrained spanning trees and capacitated minimal spanning trees, and show significant improvement in scheduling performance over different deployment densities. Lastly, we evaluate the impact of different interference and channel models on the schedule length.

In this paper, a new distributed power-control (DPC) scheme is suggested to improve convergence speedand system robustness against carrier-to-interference-ratio (CIR) estimation errors. To expedite the CIR balancing in our DPC scheme, an instability detection rule was used. As compared with Foschini's DPC (FDPC) method, numerical results indicated that the proposed algorithm achieves performance improvements in terms of outage probability as well as in the algorithm's convergence speed. More specifically, by appropriate selection of some parameters, the algorithm speed reduces from about 90 iterations in FDPC to 9 iterations in the proposed algorithm. The system robustness against CIR estimation errors was also explored.

Index Terms:-Cellular systems, CIR balancing, distributed algorithms, instability detection, power control, Converge cast, TDMA scheduling, multiple channels, power-control, routing trees.

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1 INTRODUCTION:

Frequency reuse in wireless cellular networks results in increased system capacity. It increases, however, the co channel interference that imposes limitations on the minimum reuse distance. An efficient technique in reducing the co channel interference is to control the transmitted power in order to provide each receiver with a satisfactory reception. A commonly used measure of the quality of communications is the carrier-to-interference ratio (CIR) at the receiver.

Converge cast, namely the collection of data from a set of sensors toward a common sink over a tree-based routing topology, is a fundamental operation in wireless sensor networks (WSN) [1]. In many applications, it is crucial to provide a guarantee on the delivery time as well as increase the rate of such data collection. For instance, in safety and mission-critical applications where sensor nodes are deployed to detect oil/gas leak or structural damage, the actuators and controllers need to receive data from all the sensors within a specific deadline [2], failure of which might lead to unpredictable and catastrophic events.

The following lists our key findings and contributions:

• **Bounds on Converge cast Scheduling**: We show that if all interfering links are eliminated, the schedule length for aggregated converge cast is lower bounded by the maximum node degree in the routing tree, and for raw-data converge cast by max(2nk−1,N), where n k is the maximum number of nodes on any branch in the tree, and N is the number of source nodes. We then introduce optimal time slot assignment schemes under this scenario which achieve these lower bounds.

• **Evaluation of Power Control under Realistic Setting:** It was shown recently [5] that under the idealized setting of unlimited power and continuous range, transmission power control can provide an unbounded improvement in the asymptotic capacity of aggregated converge cast. In this work, we evaluate the behavior of an optimal power control algorithm [6] under realistic settings considering the limited discrete power levels available in today's radios. We find that for moderate size networks of 100 nodes power control can reduce the schedule length by 15 − 20%.

• **Evaluation of Channel Assignment Methods:** Using extensive simulations, we show that scheduling transmissions on different frequency channels is more effective in mitigating interference as compared to transmission power control. We evaluate the performance of three different channel assignment methods: (i) Joint Frequency and Time Slot Scheduling (JFTSS), (ii) Receiver-Based Channel Assignment (RBCA) [7], and (iii) Tree-Based Channel Assignment (TMCP) [8]. These methods consider the channel assignment problem at different levels: the link level, node level, or cluster level. We show that for aggregated converge cast, TMCP performs better than JFTSS and RBCA on minimum-hop routing trees, while performs worse on degree-constrained trees.

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For raw-data converge cast, RBCA and JFTSS perform better than TMCP, since the latter suffers from interference inside the branches due to concurrent transmissions on the same channel.

• **Impact of Routing Trees**: We investigate the effect of network topology on the schedule length, and show that for aggregated converge cast the performance can be improved by up to 10 times on degree constrained trees using multiple frequencies as compared to that on minimum-hop trees using a single frequency. For raw-data converge cast, multi-channel scheduling on capacitated minimal spanning trees can reduce the schedule length by 50%.

• **Impact of Channel Models and Interference**: Under the setting of multiple frequencies, one simplifying assumption often made is that the frequencies are orthogonal to each other. We evaluate this assumption and show that the schedules generated may not always eliminate interference, thus causing considerable packet losses. We also evaluate and compare the two most commonly used interference models: (i) the graph-based protocol model, and (ii) the SINR (Signal-to-Interference-plus-Noise Ratio) based physical model.

Periodic collection of aggregated data from sensors to a common sink over a tree topology is a fundamental operation in wireless sensor networks (WSN). In many such applications, it is of interest to maximize the rate at which the sink can receive aggregated data from the network [1]. For instance, it has been noted that in networked structural health monitoring more than 500 samples per second are required to efficiently detect damages [2]. Time division multiple access (TDMA) scheduling is a natural solution for such periodic data collection applications [3], [4]. Consider a repeated frame of k time slots in which each link of the data gathering tree is scheduled once. In steady state (once a pipeline is established), the sink will receive aggregated information from all nodes in the network once per frame, i.e. once every k slots. In this framework, maximizing the data collection rate corresponds exactly to minimizing the frame length. This is the focus of our work.

We explore a number of techniques in order to address the basic question: "how fast can aggregate data be streamed to the sink"? These techniques provide a hierarchy of successive improvements. The simplest approach is to do some form of interference-aware minimum frame-length TDMA-scheduling that enables spatial reuse. The second step is to combine the scheduling with transmission power control. The third step is to consider the use of multiple frequency channels. We show that once multiple frequencies are employed along with spatial-reuse TDMA, the aggregated data collection rate often becomes no longer interference-limited, but rather topology limited. Thus, the final step to enhance the rate of periodic aggregated data collection is to use an appropriate degree constrained tree topology. Our primary conclusion is that combining these techniques can provide an order of magnitude improvement in the rate compared to the simple approach of TDMA

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scheduling on a single channel with minimum-hop routing trees.

In the present paper, we present a new DPC algorithm that achieves CIR balancing with unit probability. Numerical analysis through computer simulations indicated that our algorithm, in conjunction with the use of the instability detection rule, has excellent performance compared to Foschini's DPC algorithm (FDPC) in terms of outage probability and convergence speed.

2. RELATED WORKS:

We experimentally investigated the impact of transmission power control and multiple frequency channels on the schedule length; we proposed constant factors and logarithmic approximation algorithms on geometric networks (disk graphs). Frequency reuse in wireless cellular networks results in increased system capacity. It increases, however, the co channel interference that imposes limitations on the minimum reuse distance. An efficient technique in reducing the co channel interference is to control the transmitted power in order to provide each receiver with a satisfactory reception. A commonly used measure of the quality of communications is the carrier-to-interference ratio (CIR) at the receiver.

For raw-data converge cast, Song et al. [12] presented a time-optimal, energy-efficient, packet scheduling algorithm with periodic traffic from all the nodes to the sink. Once interference is eliminated, their algorithm achieves the bound that we present here, however, they briefly mention a 3-coloring channel assignment scheme, and it is not clear whether the channels are frequencies, codes, or any other method to eliminate interference. Moreover, they assume a simple interference model where each node has a circular transmission range and cumulative interference from concurrent multiple senders is avoided. Different from their work, we consider multiple frequencies and evaluate the performance of three different channel assignment methods together with evaluating the effects of transmission power control using realistic interference and channel models, i.e., physical interference model and overlapping channels and considering the impact of routing topologies. Song et al. [12] extended their work and proposed TDMA based MAC protocol for high data rate WSNs in [16]. Tree MAC considers the differences in load at different levels of a routing tree and assigns time slots according to the depth, i.e. the hop count, of the nodes on the routing tree, such that nodes closer to the sink are assigned more slots than their children in order to mitigate congestion. However, Tree MAC operates on a single channel and achieves 1/3 of the maximum throughput similar to the bounds presented by Gandham et al. [1] since the sink can receive every 3 time slots. The problem of minimizing the schedule length for raw-data converge cast on single channel is shown to be NP-complete on general graphs by Choi et al. [13]. Maximizing the throughput of converge cast by finding a shortest-length, conflict free schedule is studied by Lai et al. [14], where a greedy graph coloring strategy assigns time slots to the senders and prevent interference. They also discussed the impact of routing trees on the schedule length and

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proposed a routing scheme called disjoint strips to transmit data over different shortest paths. However, since the sink remains as the bottleneck, sending data over different paths does not reduce the schedule length. As we will show in this paper, the improvement due to the routing structure comes from using capacitated minimal spanning trees for raw-data converge cast, where the number of nodes in a sub tree is no more than half the total number of nodes in the remaining sub trees. The use of multiple frequencies has been studied extensively in both cellular and ad hoc networks, however, in the domain of WSN, there exist a few studies that utilize multiple channels [8], [17], [18]. To this end, we evaluate the efficiency of three particular schemes that treat the channel assignment at different levels.

3. MECHANISMS

A. Preliminaries

Before explaining the studied mechanisms, we first express the preliminary design details and assumptions:

• We consider a static wireless sensor network. The sensor nodes periodically sense the environment and send their readings over a multi-hop tree topology.

• Time is divided into equal sized slots that are grouped into frames. We focus on minimizing the length of the frame such that each node is assigned one time slot.

• We consider minimum-hop routing trees where all the nodes select a parent node where they transmit their readings to be forwarded towards the sink node.

• We assume all the nodes in the network are sources and the data is aggregated such that the data coming from different sources are combined into a packet(s) before forwarding. If the incoming packets cannot be combined in a single packet and multiple packets have to be forwarded, we assume each time slot is long enough to transmit those packets. This is a reasonable assumption since the size of the sensor readings is usually very small. Figure 1 shows the relationship between the schedule length and the aggregated data rate. The numbers on the links show the assigned time slots and the numbers inside the circles represent the node id's. On the left of the figure we see the schedule showing the received packets from the associated senders by each parent on each time slot. After frame 1, once the sink gets initial data from each source (a pipeline is established), the same schedule is repeated and the sink collects the aggregated data from the network at a rate of 3 time slots. Thus, the schedule length should be minimized to improve the data collection rate.

	Frame 1			Frame 2		
Receiver	slot 1	slot 2	slot 3	slot 1	slot 2	slot 3
Sink	3	1,4	2, 5, 6	3, 7	1, 4	2, 5, 6
Node 1	4			4		
Node 2	5	6		5	6	
Node 3		7			7	

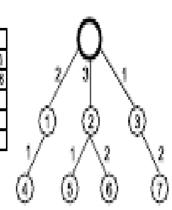

Fig. 1. Relationship between data collection rate and schedule length

B. Joint Scheduling and Power Control:

A cross layer method for joint scheduling and power control in wireless multi-hop

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networks. They proposed an optimal distributed algorithm to improve the throughput capacity of wireless networks. The aim is to find a TDMA schedule which can support as many transmissions as possible in each time slot. We use their algorithm to investigate the impact of power control on the scheduling performance.

The solution is composed of 2 phases: scheduling and power control. It is to be executed at the beginning of each time slot in order to cope with excessive interference levels. The scheduling phase searches for a transmission schedule which is defined to be valid if no node is to transmit and receive simultaneously and no node is to receive from more than one neighbor at the same time. Power control phase iteratively searches for an admissible schedule which means that a set of transmission powers is available to satisfy the SINR (signal to interference and noise ratio) constraints for all links in the given valid schedule. In each iteration nodes adjust their transmission powers as follows:

=*

Where the new transmission power level in the next iteration is, is the current transmission power level and β is the SINR threshold. If the maximum number of iterations is reached and still there are nodes which cannot meet the SINR constraints, i.e., if the valid scenario is not admissible, the scheduling algorithm excludes the link with the minimum SINR. The power control algorithm is repeated until an admissible transmission scenario is found. Then, the nodes start transmission using the computed transmission powers in the current slot.

C. Frequency and Time Scheduling

The use of multiple frequency channels is an efficient way to improve the capacity of wireless networks. Simultaneous transmissions on different frequencies (if the frequencies are not orthogonal, different frequencies may also be conflicting. We use non-conflicting frequencies and different frequencies interchangeably in the text) can take place without interference in the same spatial neighborhood.

In this section we introduce a simple scheduling method which separately assigns the time slots and frequencies on a tree topology. Motivation for this proposal is as follows:

• Intersecting links, which are defined as the links with a common destination (Figure 2), cannot transmit on the same time slot since they have to wait for each other's transmission. Assigning non conflicting frequencies to these nodes does not improve the situation, either. Then the receiver should be assigned a frequency and the senders should use this frequency to transmit to the parent.

• Interfering links are the links which create/face interference if they are scheduled simultaneously. Figure 2 shows an example where the dotted line represents interference. Interfering links should not get the same time slot and frequency. Since our aim is to minimize the number of time slots, the best option then is to assign the same time slot on non-conflicting frequencies.

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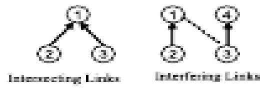

Fig. 2. Intersecting and Interfering Links

The method is composed of 2 phases: frequency scheduling and time slot scheduling. In the frequency scheduling phase, the receivers, i.e. the parents on the tree, are assigned frequencies. The goal of the frequency assignment phase is to schedule the interfering links on non-conflicting frequencies such that the receptions at the parents of the interfering senders are not disturbed. Initially, all the nodes operate on the same frequency. The method collects information about the interfering links (we consider both graph based and SINR based interference models and present the results in Section V). According to the collected information, at each step the most interfered parent (the parent with the highest number of interfering links) is assigned a frequency, if one is available. If not, the parent node and the associated children remain on the initial frequency and the interference conflicts have to be solved in the time slot assignment phase.

After the frequency scheduling, the algorithm continues with the time slot assignment to the senders. Similar to the power control approach, a node can be scheduled such that it cannot transmit and receive simultaneously and cannot receive from more than one neighbor at the same time, due to the transceiver Limiations. If the parents of all interfering senders could be assigned different frequencies (this means the interference is totally eliminated), we can skip the SINR check. If not, during the time slot assignment, the SINR condition is checked among the interfering senders.

Figure 3 shows a scheduling example on a tree topology. In the first part of the figure, the solid lines between the nodes show the transmission links whereas the dotted lines show the interfering links. The numbers inside the circles represent the node id's. The second part of the figure shows the tree after time slot assignment with a single frequency channel. The numbers on the links show the assigned time slots. In this case, it takes 6 time slots to schedule the network. In the third part of the figure we see how the scheduling is performed with 2 frequencies. First, the frequencies are assigned to the parents (represented inside the boxes next to each parent, $F1$ is the initial frequency). Then, the time slots are assigned to the senders. With 2 frequencies, the network is scheduled in 4 slots. The last part shows the case with 3 frequencies. The network is then scheduled in 3 time slots. We achieve a %50 reduction on the schedule length thus the data collection rate at the sink node is doubled with the sufficient number of frequencies.

The receiver based frequency assignment makes the algorithm suitable for tree topologies and avoids the overhead of frequent frequency switching for the transceiver since the nodes switch at most between 2 frequencies. It may be argued that, an interfering link does not always disturb all the children of a parent node. Thus, assigning a frequency to a parent limits the communication possibilities for those children. To investigate this issue, by extensive simulations, we compared the performance of our algorithm with a different approach where each sender is assigned a time slot and a frequency. The performance is observed to be similar; however we cannot present the results in this paper due to the space limitations.

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D. Routing Strategies, Parent Selection

In the previous sections we have discussed the methods to cope with interference. Other than interference, connectivity may also limit the performance of scheduling. Consider the nodes that select the same parent. They have to wait for each others'

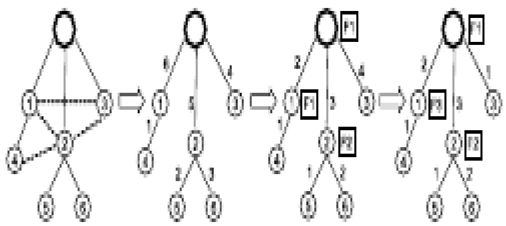

Fig. 3. Frequency and Time Scheduling on a Minimum-Hop Routing Tree

transmission which simply increases the length of a schedule. In this section we investigate the methods that can adjust the degree of connectivity on a tree topology.
One option would be to construct balanced trees. We compared the scheduling performance on minimum-hop balanced and unbalanced trees. However, no improvement is observed with balanced trees since the sink node often remains the high-degree bottleneck (due to the space limitations we cannot represent the results in this paper). To avoid the bottlenecks, there should be a limitation on the number of children per parent. Thus, we explore scheduling on degree constrained tree topologies.
A degree-constrained minimum-hop tree is constructed using a modified version of Dijkstra's shortest path algorithm. Consider a graph G(V, E) and a given degree constraint max degree. Each node n keeps a value for the number of its children C (n) with an initial value = 0 and hop count to the sink HC (n) with an initial value = ∞. The algorithm starts with a set T that contains the sink node s (HC(s) =0), at each iteration we add a node m ∈ T to T with the following constraints:

- There is a node m'∈ Tsuch that edge (m, m') ∈ E,
- C (m') <m a x_degree -1,
- The hop count to the sink =HC (m) is minimized.

The updates are made as HC(m)= HC(m')+1 and C(m')=C(m')+1. The algorithm stops when |T| = |V | or when no more nodes can be added since the degree of the all nodes in T have reached the max degree.

To clarify the gains with this method, consider the case when all n nodes are in range of each other and the sink. If the nodes select their parents according the minimum hop criteria without a degree constraint, all the nodes will select the sink as a parent and this schedule will take n time slots. On the other hand, if we limit the number of connections per node as 2,t h i s will result in 2 sub trees rooted at the sink. If there is enough number of frequencies to eliminate all the interference then the network can be scheduled in 2 time slots and we achieve a factor of n/2 reduction in the schedule length. Figure 4 shows the same network as in Figure 3 with a different routing tree where the degree of a node is constrained to 2. The second part of the figure shows the time slot scheduling which takes 4 time slots on a single channel frequency. The last part shows when time slots are scheduled over different frequency channels. This takes 2 time slots to schedule all the links which is "3" times better than the baseline with a single frequency over a non-degree constrained tree, given in Figure 3.

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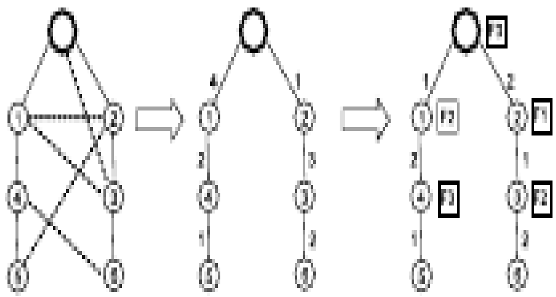

Fig. 4. Scheduling on a Degree Constrained Tree

4. MODELS FOR DESIGN

A. Interference Models

As we discussed in the introduction, there are two different interference models that are commonly used in the literature: protocol model and the physical model. According to the protocol model the transmission from a node i to a node j is successful, if for every other node k simultaneously transmitting, the following condition holds

$d(k, j) \geq (1 + \Delta)d(i, j), (\Delta > 0)$

where d(i, j) is the distance between nodes i and j, and Δ is a guard parameter that ensures that concurrently transmitting nodes are sufficiently further away from the receiver to prevent excessive interference.

On the other hand, physical model is an SINR based model that takes into account multiple transmissions. Given a transmission from node i to node j, the SINR value at receiver j is computed as follows:

$$SINR_{ij} = \frac{\alpha_{ij} P_i}{N_j + \sum_{k \neq i} \alpha_{kj} P_k}$$

where α is the path loss factor, Pi and Pk are the transmission powers for i and k, and N j is the amount of ambient noise experienced by receiver j. Transmission is successful if the corresponding SINR at receiver j is above the threshold value:

$$SINR_{ij} \geq \beta$$

Where β is the SINR threshold. In Section V-B.1, we investigate the correctness of the graph based model and the effects of the both models on scheduling performance.

B. Orthogonal Frequencies vs. Interfering Frequencies

In the current literature on multi-channel protocols, mostly either it is assumed that the channels are perfectly orthogonal (interference-free) or the use of overlapping channels is simply avoided. Assumption of perfect orthogonal channels fails in practice since radio signals are not bound to a single point in the spectrum but are distributed around a mid frequency so that channel overlap/interference is observed between adjacent bands. On the other hand, the use of only orthogonal channels cannot utilize the spectrum efficiently. For instance, the 802.11b standards dine 11 channels of which only three are orthogonal. Careful use of not only 3 channels but all 11 channels by controlling the interference can significantly improves the system performance [7].

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Interference between overlapping channels is influenced by the transmission power, distance between transmitters, channel spacing and transceiver characteristics [8]. In Section V, we compare the impact of orthogonal frequencies and interfering frequencies on the scheduling performance for two different transceiver platforms. Moreover, we investigate the correctness of schedules generated with the orthogonal frequencies assumption.

5. TDMA SCHEDULING OF CONVERGECASTS

In this section, we first focus on periodic aggregated converge cast and then on one-shot raw-data converge cast. Our objective is to calculate the minimum achievable schedule lengths using an interference-aware TDMA protocol. We first consider the case where the nodes communicate on the same channel using a constant transmission power, and then discuss improvements using transmission power control and multiple frequencies in the next section.4.1 Periodic Aggregated Converge cast In this section, we consider the scheduling problem where packets are aggregated. Data aggregation is a commonly used technique in WSN that can eliminate redundancy and minimize the number of transmissions,

Thus saving energy and improving network lifetime [19]. Aggregation can be performed in many ways, such as by suppressing duplicate messages; using data compression and packet merging techniques; or taking advantage of the correlation in the sensor readings.

We consider continuous monitoring applications where perfect aggregation is possible, i.e., each node is capable of aggregating all the packets received from its children as well as that generated by itself into a single packet before transmitting to its parent. The size of aggregated data transmitted by each node is constant and does not depend on the size of the raw sensor readings. Typical examples of such aggregation functions are MIN, MAX, MEDIAN, COUNT, AVERAGE, etc.

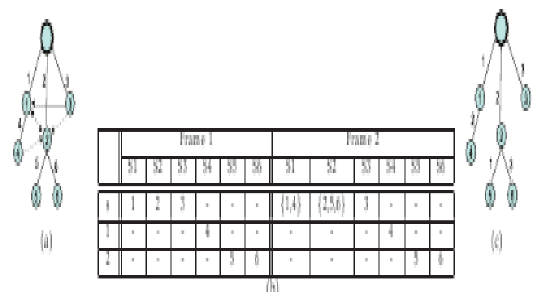

Fig. 1: Aggregated converge cast and pipelining: (a) Schedule length of 6 in the presence of interfering links. (b) Node ids from which (aggregated) packets are received by their corresponding parents in each time slot over different frames. (c) Schedule length of 3 using BFS-TIMESLOTASSIGNMENT when all the interfering links are eliminated.

In Fig. 1(a) and1 (b), we illustrate the notion of pipelining in aggregated converge cast and that of a schedule length on a network of 6 source nodes. The solid lines represent tree edges, and the dotted lines represent interfering links. The numbers beside the links represent the time slots at which the links are scheduled to transmit, and the numbers inside the circles denote node ids.

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The entries in the table list the nodes from which packets are received by their corresponding receivers in each time slot. We note that at the end of frame 1, the sink does not have packets from nodes 5 and 6; however, as the schedule is repeated, it receives aggregated packets from 2, 5, and 6 in slot 2 of the next frame. Similarly, the sink also receives aggregated packets from nodes 1 and 4 starting from slot 1 of frame 2. The entries {1, 4} and {2, 5, 6} in the table represent single packets comprising aggregated data from nodes1 and 4, and from nodes2, 5, and 6, respectively. Thus, a pipeline is established from frame 2, and the sink continues to receive aggregated packets from all the nodes once every 6 time slots. Thus, the minimum schedule length is 6.

6. IMPACT OF INTERFERENCE

So far, we have focused on computing spatial-reuse TDMA schedules where transmissions take place on the same frequency at a constant transmission power. In this section, we focus on different methods to mitigate the effects of interference on the schedule length. First, we discuss the benefits of using transmission power control and explain the basics of a possible algorithm. Then we discuss the advantages of using multiple channels by considering 3 different channel assignment schemes.

6.1 Transmission Power Control

In wireless networks, excessive interference can be eliminated by using transmission power control [6], [20], i.e., by transmitting signals with just enough power instead of maximum power. To this end, we evaluate the impact of transmission power control on fast data collection using discrete power levels, as opposed to a continuous range where an unbounded improvement in the asymptotic capacity can be achieved by using a non-linear power assignment [5]. We first explain the basics of one particular algorithm that we use in our
evaluations in Section 7.

The algorithm proposed by El Batt et al. [6] is a cross layer method for joint scheduling and power control and it is an optimal distributed algorithm to improve the throughput capacity of wireless networks. The goal is to find a TDMA schedule that can support as many transmissions as possible in every time slot. It has two phases: (i) Scheduling and (ii) power control that are executed at every time slot. First the scheduling phase searches for a valid transmission schedule, i.e., largest subset of nodes, where no node is to transmit and receive simultaneously, or to receive from multiple nodes simultaneously. Then, in the given valid schedule the power control phase iteratively searches for an admissible schedule with power levels chosen to satisfy all the interfering constraints. In each iteration, the scheduler adjusts the power levels depending on the current RSSI at the receiver and the SINR threshold according to the iterative rule: P new = β SINR·P current .According to this rule, if a node transmits with a power level higher than what is required by the threshold value, it should decrease its power and if it is below the threshold it should increase its transmission power, within the available

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range of power levels on the radio. If all the nodes meet the interfering constraint, the algorithm proceeds with the schedule calculation for the next time slot. On the other hand, if the maximum number of iterations is reached and there are nodes which cannot meet the interfering constraint, the algorithm excludes the link with minimum SINR from the schedule and restarts the iterations with the new subset of nodes. The power control phase is repeated until an admissible transmission scenario is found.

6.2 Multi-Channel Scheduling

Multi-channel communication is an efficient method to eliminate interference by enabling concurrent transmissions over different frequencies [21]. Although typical WSN radios operate on a limited bandwidth, their operating frequencies can be adjusted, thus allowing more concurrent transmissions and faster data delivery. Here, we consider fixed-bandwidth channels, which are typical of WSN radios, as opposed to the possibility of improving link bandwidth by consolidating frequencies. In this section, we explain three channel assignment methods that consider the problem at different levels allowing us to study their pros and cons for both types of converge cast. These methods consider the channel assignment problem at different levels: the link level (JFTSS), node level (RBCA), or cluster level (TMCP).

6.2.1 Joint Frequency Time Slot Scheduling (JFTSS)

JFTSS offers a greedy joint solution for constructing a maximal schedule, such that a schedule is said to be maximal if it meets the adjacency and interfering constraints, and no more links can be scheduled for concurrent transmissions on any time slot and channel without violating the constraints. Approximation bounds on JFTSS for single-channel systems and its comparison with multi-channel systems are discussed in [22] and [23], respectively.

JFTSS schedules a network starting from the link that has the highest number of packets (load) to be transmitted. When the link loads are equal, such as in aggregated converge cast, the most constrained link is considered first, i.e., the link for which the number of other links violating the interfering and adjacency constraints when scheduled simultaneously is the maximum. The algorithm starts with an empty schedule and first sorts the links according to the loads or constraints. The most loaded or constrained link in the first available slot-channel pair is scheduled first and added to the schedule. All the links that have an adjacency constraint with the scheduled link are excluded from the list of the links to be scheduled at a given slot. The links that do not have an interfering constraint with the scheduled link can be scheduled in the same slot and channel whereas the links that have an interfering constraint should be scheduled on different channels, if possible. The algorithm continues to schedule the links according to the most loaded (or most constrained) metric. When no more links can be scheduled for a given slot, the scheduler continues with scheduling in the next slot. Fig. 4(a) shows the same tree

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given in Fig. 1(a) which is scheduled according to JFTSS where aggregated data is collected. JFTSS starts with link (2, sink) on frequency 1 and then schedules link (4,1) next on the first slot on frequency 2. Then, links (5, 2) on frequency 1 and (1, sink) on frequency 2 are scheduled on the second slot and links (6, 2) on frequency 1 and(3, sink) on frequency 2 are scheduled on the last slot.

An advantage of JFTSS is that it is easy to incorporate the physical interference model, however, it is hard to have a distributed solution since the interference relationship between all the links must be known.

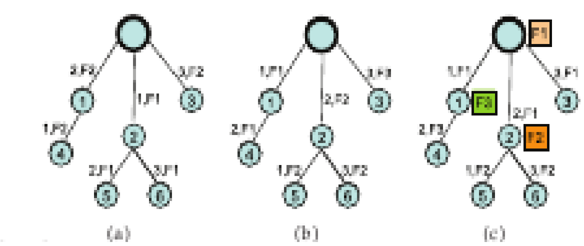

Fig. 4: Scheduling with multi-channels for aggregated converge cast:
(a) Schedule generated with JFTSS. (b) Schedule generated with TMCP.
(c) Schedule generated with RBCA. (b) Schedule generated with RBCA.

6.2.2 Tree-Based Multi-Channel Protocol (TMCP)

TMCP is a greedy, tree-based, multi-channel protocol for data collection applications [8]. It partitions the network into multiple sub trees and minimizes the intra tree interference by assigning different channels to the nodes residing on different branches starting from the top to the bottom of the tree. Figure 4(b) shows the same tree given in Fig. 1(a) which is scheduled according to TMCP for aggregated data collection. Here, the nodes on the leftmost branch is assigned frequency F1, second branch is assigned frequency F2 and the last branch is assigned frequency F3 and after the channel assignments, time slots are assigned to the nodes with the BFS-Time Slot Assignment algorithm. The advantage of TMCP is that it is designed to support converge cast traffic and does not require channel switching. However, contention inside the branches is not resolved since all the nodes on the same branch communicate on the same channel.

6.2.3 Receiver-Based Channel Assignment (RBCA)

In our previous work [7], we proposed channel assignment method called RBCA where we statically assigned the channels to the receivers (parents) so as to remove as many interfering links as possible. In RBCA, the children of a common parent transmit on the same channel. Every node in the tree, therefore, operates on at most two channels, thus avoiding pair-wise, per-packet, channel negotiation overheads. The algorithm initially assigns the same channel to all the receivers. Then, for each receiver, it creates a set of interfering parents based on SINR thresholds and iteratively assigns the next available channel starting from the most interfered
parent (the parent with the highest number of interfering links). However, due to adjacent channel overlaps, SINR values at the receivers may not always be high enough to tolerate interference, in which case the channels are assigned according to

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the ability of the transceivers to reject interference. We proved approximation factors for RBCA when used with greedy scheduling in [9]. Fig- ure 4(c) shows the same tree given in Fig. 1(a) scheduled with RBCA for aggregated converge cast. Initially all nodes are on frequency F1. RBCA starts with the most interfered parent, node 2 in this example, and assigns F2. Then it continues to assign F3 to node 3 as the second most interfered parent. Since all interfering parents are assigned different frequencies sink can receive on F1.

7. IMPACT OF ROUTING TREES

Besides transmission power control and multiple channels, the network topology and the degree of connectivity also affect the scheduling performance. In this section, we describe schemes to construct topologies with specific properties that help to reduce the schedule length.

7.1 Aggregated Data Collection

We first construct balanced trees and compare their performance with unbalanced trees. We observe that in both cases the sink often creates a high-degree bottleneck. To overcome this, we then propose a heuristic, as described in Algorithm 3, by modifying Dijkstra's shortest path

Algorithm to construct degree-constrained trees Note that constructing such a degree-constrained tree is NP-hard. Each source node i in our heuristic keeps track of the number of its children, C(i), which is initialized to 0, and a hop count to the sink, HC(i), which is initialized to∞. The algorithm starts with the sink node, and adds a node I 簃 □∈ T at every iteration to the tree such that HC(i睷) is minimized. It stops when |T| = |V |, or when no more nodes can be added to the tree because the neighbors of all these new nodes have reached the limit on their maximum degree. Consequently, in this latter situation, the heuristic might not always generate a spanning tree. In our evaluation presented in Section 7.3, we consider only those instances of the topologies where spanning trees with the specified degree constraint are produced. To illustrate the gains of degree-constrained trees, consider the case when all the N nodes are in range of each other and that of the sink. If the nodes select their parents according to minimum-hop without a degree constraint, then all of them will select the sink, and this will give a schedule length of N. However, if we limit the number of children per node to 2, then this will result in two sub trees rooted at the sink, and if there are enough frequencies to eliminate interference, the network can be scheduled using only 2 time slots, thus achieving a factor
of N/2 reduction in the schedule length.

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Algorithm 3 DEGREE-CONSTRAINED TREES

```
Input: G(V, E), s, max_degree
T ← {s}
for all i ∈ V do
    C(i) ← 0; HC(i) ← ∞
end for
HC(s) ← 0
while |T| ≠ |V| do
    Choose i' ∉ T such that:
        (a) (i, i') ∈ E, for some i ∈ T with C(i) < max_degree -
        (b) HC(i') is minimized
    T ← T ∪ {i'}
    HC(i') = HC(i) + 1
    C(i) ← C(i) + 1
    if ∀i ∈ V, C(i) = max_degree then
        break
    end if
end while
```

Algorithm 4 CAPACITATED-MINIMALSPANNINGTREE

```
Input: G(V, E), s
Initialize:
    B ← roots of top subtrees        // the branches
    T ← {s} ∪ B
    ∀i ∈ V, GS(i) ← unconnected neighbors of i at further hops
    ∀b ∈ B, W(b) ← 1
    h ← 2
while h ≠ max_hop_count do
    N_h ← unconnected nodes at hop distance h
    Connect nodes N'_h that have a single potential parent: T ←
    T ⋃ N'_h
    Update N_h ← N_h \ N'_h
    Sort N_h in non-increasing order of |GS|
    for all i ∈ N_h do
        for all b ∈ B to which i can connect do
            Construct SS(i, b)
        end for
        Connect i to b for which W(b) + |SS(i, b)| is minimum
        Update GS(i) and W(b)
        T ← T ⋃ {i} ⋃ SS(i, b)
    end for
    h ← h + 1
end while
```

7.2 Raw Data Collection

As emphasized in [13], routing trees that allow more parallel transmissions do not necessarily result in small schedule lengths. For instance, the schedule length is N for a network connected as a star topology, whereas it is (2N −1) for a line topology once interference is eliminated. Theorem 1 suggests that the routing tree should be constructed such that all the branches have a balanced number of nodes and the constraint nk< (N +1) /2holds. In this section, we construct such routing trees.

A balanced tree satisfying the above constraint is a variant of a capacitated minimal spanning tree (CMST) [24]. The CMST problem, which is known to be NP-complete, is to determine a minimum-hop spanning tree in a vertex weighted graph such that the weight of every sub tree linked to the root does not exceed a prescribed capacity. In our case, the weight of each link is 1, and the prescribed capacity is (N +1) /2. Here, we propose a heuristic, as described in Algorithm 4, based on the greedy scheme presented by Dai et al. [25], which solves a variant of the CMST problem by searching for routing trees with an equal number of nodes on each branch. We augment their scheme with a new set of rules and grow the tree hop by hop outwards from the sink. We assume that the nodes know their minimum-hop counts to sink.

Rule 1: Nodes with single potential parents are connected first.

Rule 2: For nodes with multiple potential parents, we first construct their growth sets (GS) and choose the one with the largest cardinality for further processing, breaking ties based on the smallest id. We define the growth set of a node as the set of neighbors (potential children) that are not yet connected to the tree and have larger hop counts.

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Rule 3: Once a node is chosen based on the growth sets according to Rule 2, we construct search sets (SS)to decide which potential branch the node should be added to. A search set is thus branch-specific and includes the nodes that are not yet connected to the tree and are neighbors of a node that are at a higher hop count. In particular, if the chosen node has access to branch b, and has a neighbor that can connect to only branch b if b is selected, then this neighbor and its potential children are included in the search set for b. However, if the neighbor

has access to at least one other branch even after b is selected, then it is not included in the search set.

The search sets guarantee that the choices for the nodes at longer hops to join a particular branch are not limited by the decision of the joining node. This balances out the number of nodes on different branches and prevents one to grow faster than others. Once the search sets are constructed, we choose the branch for which the sum of its load (W) and the size of the search set is minimum.

To illustrate the merit of search sets, consider the situation. Dotted lines represent potential communication links and solid lines represent already included tree edges. At this point, node 4 is being processed, and the loads on branches b1 and b2 are 2 and 4, respectively, where bi denote the branch rooted at node i. The search set SS(4,b1) is {8,9,10}, because the neighbor node 8 has access to only b1 if b1 is selected by node 4. However, the search set SS(4,b2) is empty, because the neighbor node 8 has access to another branch b1 (via node 3). Therefore, the sum of the load and the size of the search set for b1 is 5, and that for b2 is 4. So we attach node 4 to b2, and in the next step attach node 8t ob1. This balances out the number of nodes over the two branches.

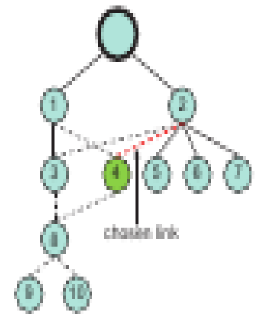

Fig. : Balanced tree construction: Node 4 is attached to b2

based on the search sets; load on both b1 and b2 is 5

8. CONCLUSIONS

In this paper, we studied fast converge cast in WSN where nodes communicate using a TDMA protocol to minimize the schedule length. We addressed the fundamental limitations due to interference and half-duplex transceivers on the nodes and explored techniques to overcome the same. We found that while transmission power control helps in reducing the schedule length, multiple channels are more effective. We also observed that node-based (RBCA) and link-based (JFTSS) channel assignment schemes are more efficient in terms of eliminating interference as compared to assigning different channels on different branches of the tree (TMCP).

Once interference is completely eliminated, we proved that with half-duplex radios the achievable schedule length is lower-bounded by the maximum degree in the routing tree

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for aggregated converge cast, and by max (2nk− 1,N) for raw-data converge cast. Using optimal converge cast scheduling algorithms, we showed that the lower bounds are achievable once a suitable routing scheme is used. Through extensive simulations, we demonstrated up to an order of magnitude reduction in the schedule length for aggregated, and a 50% reduction for raw-data converge cast. In future, we will explore scenarios with variable amounts of data and implement and evaluate the combination of the schemes considered.

We have explored a number of techniques to enhance the aggregated data collection over a tree topology in WSN. Our initial approach was to use interference-aware minimum frame-length TDMA-scheduling that enables spatial reuse. The second step was to combine the scheduling with transmission power control. Although the well studied transmission power control method helped to overcome interference and reduce schedule length, it was found to be not always the best solution in a practical setting due to the limitations on the power settings of the nodes. The next step was to consider the use of multiple frequency channels. With the extensive simulations we found that for networks of about a hundred nodes, the use

of multi-frequency scheduling can suffice to eliminate most of the interference. Then, data collection rate was no longer interference-limited, but rather topology-limited. Thus, our final approach was to use an appropriate degree-constrained tree construction. Simulation results showed that, combining the last two techniques can provide an order of magnitude improvement compared to the simple approach of scheduling on a single channel with minimum-hop routing trees.

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