Fast Data Collection in Ring-Based Wireless Sensor Networks

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Abstract— **We search out the fundamental question - how fast can data be collected from a wireless sensor network organized as ring? To solve this problem we evaluate a number of different techniques using simulation models under the communication paradigm known as convergecast. 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 convergecast. 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 effective. We give lower bounds on the schedule length when interference is completely removed, and propose algorithms that achieve these bounds. We also evaluate the performance of various channel assignment methods and search 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 ring. To this end, we construct degree-constrained spanning ring and capacitated minimal spanning ring 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.**

Index Terms— **Converge cast, TDMA scheduling, multiple channels, power-control, routing rings.**

I. INTRODUCTION

CONVERGECAST, namely the gathering of data from a set of sensors toward a common sink over a ring based routing topology, is a fundamental operation in wireless sensor networks (WSN). 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 gas leak or structural damage, the actuators and controllers need to receive data from all the sensors within a specific time, failure of which might lead to catastrophic events. This falls under the category of one-shot data collection. On the other hand, applications such as permafrost monitoring require periodic and fast data delivery over long periods of time, which falls under the category of data collection

In this paper, we consider such applications and focus on the following question" How fast can data be collected from a set of sensors to a sink over a ring based topology?" We study two types of data collection: (i) aggregated convergecast where packets are aggregated at Each hop, and (ii) raw-data convergecast where packets are Individually relayed toward the sink. Aggregated converge cast is applicable when a strong spatial correlation exists in the data or the goal is to collect summarized information such as the maximum sensor reading. Raw data convergecast, on the other hand, is applicable when every sensor reading is equally important, or the correlation is minimal. We study aggregated convergecast in the context of continuous data collection, and raw data convergecast for one-shot data collection. These two types correspond to two extreme cases of data collection. In an earlier work , the problem of applying different aggregation factors, i.e., data compression factors, was studied, and the latency of data collection was shown to be within the performance bounds of the two extreme cases of no data compression (raw-data convergecast) and full data compression (aggregated convergecast).

For periodic traffic, it is well known that contention free medium access control (MAC) protocols such as TDMA (Time Division Multiple Access) are better fit for fast data collection, since they can eliminate collisions and retransmissions and provide guarantee on the completion time as opposed to contention-based protocols [1]. However, the problem of constructing conflict free (interference-free) TDMA schedules even under the simple graph-based interference model has been proved to be NP-complete. In this work, we consider a TDMA frame work and design polynomial-time heuristics to Minimize the schedule length for both types of converge cast. We also find lower bounds on the achievable Schedule lengths and compare the performance of our Heuristics with these bounds.

We start by identifying the primary limiting factors of fast data collection, which are: (i) *interference* in the wireless medium, (ii) *half-duplex/full duplex* transceivers on the sensor nodes, and (iii) *topology* of the network. Then, we explore a number of different techniques that provide a hierarchy of successive improvements, the simplest among which is an interference-aware, minimum-length, TDMA scheduling that enables spatial reuse To achieve further improvement, we combine transmission power control with scheduling, and use multiple frequency channels to enable more concurrent transmissions. We show that once multiple frequencies are employed along with spatial-reuse TDMA, the data collection rate often no longer remains limited by interference But by the topology of the network. Thus, in the final step we construct network topologies with specific

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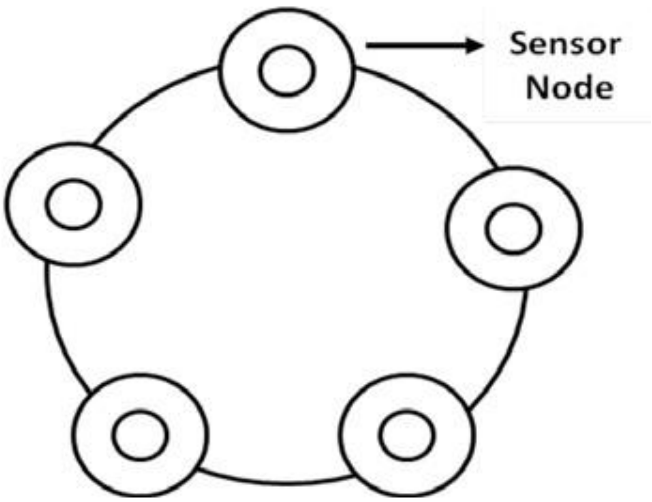
properties that help in further enhancing the rate. Our primary goal is that, combining these different techniques can provide an order of magnitude improvement For aggregated convergecast, and a factor of two improvement for raw-data convergecast, compared to single-channel and TDMA scheduling on minimum-hop routing rings.

Although the techniques of transmission power control and multi-channel scheduling have been well studied for eliminating interference in general wireless networks ,their performances for bounding the completion of data collection in WSNs have not been explored in detail in the previous studies. The fundamental novelty of our approach lies in the extensive exploration of the efficiency of transmission power control and multichannel communication on achieving fast convergecast operations in WSNs. Besides, we also calculate the impact of routing rings on fast data collection and to the best of our knowledge this has not been the topic of previously did studies. Some of the existing work had the goal of minimizing the completion time of convergecasts. However, none of the previous work discussed the effect of multi-channel scheduling together with the comparisons of different channel assignment techniques and the impact of routing rings and none considered the problems of aggregated and raw convergecast, which represent two cases of data collection, together. As the new concepts in this paper, we introduce ring based topology.



Ring topology

The following lists our key findings and contributions:

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

• **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 calculate and compare the two most commonly used interference model (i) the graph-based *protocol model*, and (ii) the SINR (Signal-to-Interference-plus-Noise Ratio) based physical model.

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

II. RELATED WORK

Fast data collection with the goal to reduce the schedule length for aggregated convergecast has been studied for tree based topology and as there are number of topologies which can be used for transfer of data .To make the study easy I applied the algorithms for ring topology as it is also used in many areas of applications.

III. MODELING AND PROBLEM FORMULATION

We model the multi-hop WSN as a ring $R = (V, E)$, where V is the set of nodes, $E = \{(i, j) \mid i, j \in V\}$ is the set of edges representing the wireless links. A designated spanning ring on R rooted as $R = (V, E_R)$, where $E_R \subseteq E$ represents the ring edges. Each node is assumed to be equipped with a single full -duplex transceiver, which allows sending and receiving packets simultaneously. We consider a TDMA protocol where time is divided into slots, Firstly we consider half duplex.

IV. TDMA SCHEDULING OF CONVERGECASTS

In this section, we first focus on periodic aggregated convergecast and then on one-shot raw-data convergecast. Our objective is to calculate the minimum achievable schedule lengths using an interference-aware TDMA protocol

A. Lower Bound on Schedule Length

We first consider aggregated convergecast when all the interfering links are eliminated by using transmission power control or multiple frequencies. Although the problem of minimizing the schedule length is NP complete on general graphs, we show in the following that once interference is eliminated, the problem reduces to one on a ring, and can be solved in polynomial time. To this end, we first give a lower bound on the schedule length, and then propose a time slot assignment scheme that achieves the bound.

LEMMA 1: If all the interfering links are eliminated, the schedule length for aggregated convergecast is lower bounded by Δ(T), where Δ(T) is the maximum node degree in the routing ring R

Proof: If all the interfering links are eliminated, the scheduling problem reduces to one on a ring. Now since each of the ring edges needs to be scheduled only once within each frame, it is equivalent to edge coloring on a graph, which needs number of colors at least equal to the maximum node degree. Once all the interfering links are eliminated, concurrency is still limited by the adjacency constraint due to the half-duplex transceivers, which prevents a parent from transmitting when it is already receiving from its children, or when its parent is transmitting

B. *Assignment of Timeslots*

Given the lower bound Δ (*T*) on the schedule length in the absence of interfering links, we now present a time slot assignment scheme in Algorithm 1, called BFSTIMESLOTASSIGNMENT that achieves this bound. In each iteration of BFS-TIMESLOTASSIGNMENT

Algorithm 1 BFS-TIMESLOTASSIGNMENT
1. Input:R = (V, ET)
2. **while** ET _= φ **do**
3. e ← next edge from ET in BFS order
4. Assign minimum time slot t to edge e respecting adjacency and
Interfering constraints
5. ET ← ET \ {e}
6. **end while**

THEOREM 1: If all the interfering links are eliminated, the Schedule length for aggregated convergecast achieved by BFSTIMESLOTASSIGNMENT is the minimum, *i.e.*, Δ(*T*).

Proof: The proof is by induction on *i*. Let *Ti* = (*V i*, *EiT*) denote the subring of *T* in the *ith* iteration constructed in the BFS order, where *EiT* comprises all the edges that are assigned a slot, and *V i* comprises the set of nodes on which the edges in *EiT* are incident. Note that, |*EiT* | = *i*, because at every iteration exactly one edge is assigned a slot. For *i* = 1, clearly the number of slots used is 1, equal to Δ(*T*1). Now, assume that the number of slots *N*(*i*) needed to schedule the edges in *Ti* is Δ(*Ti*). In the (*i* + 1)*th* iteration, after assigning a slot to the next edge in BFS order, the number of slots needed in *Ti*+1 can either remain the same as before, or increase by one. Thus, *N*(*i* + 1) = max *{N*(*i*),*N*(*i*) + 1*}* (2) If it remains the same, *N*(*i* + 1) is still the maximum degree of *Ti*+1 at end of (*i* + 1)*th* iteration. Otherwise, if it increases by one, the new edge must be incident on a node *v*∗ , common to both *Ti* and *Ti*+1, such that the number of incident edges on *v*∗ that were already assigned a time slot at the end of *ith* iteration was Δ(*Ti*). This is so because in the BFS traversal, *all* the edges incident on a node are assigned a slot first before moving on to the next node, and because the slot assigned to the new edge is the minimum possible that is different from all that already assigned to the edges incident on *v*∗ until the *ith* iteration. Thus, at the end of (*i* + 1)*th* iteration, the number of slots used *N*(*i*)+1 is equal to the number of assigned edges incident on *v*∗ which, in turn, equals Δ(*Ti*+1). This proves the inductive step. Therefore, it holds at every iteration of the algorithm until the end when *i* = |*V* | − 2, yielding a schedule length equal to the maximum degree Δ(*T*) = Δ(*T*|*V* |−1). Now, since assigning different time slots to the adjacent edges of *T* is equivalent to edge coloring *T*, which requires at least Δ(*T*) colors, the schedule length is minimum. **4.2**

C. *One-Shot Raw-Data Convergecast*

In this section, we consider one-shot data collection where every sensor reading is equally important, and so aggregation may not be desirable or even possible

Algorithm 2 LOCAL-TIMESLOTASSIGNMENT
1. node.buffer = full
2. if {node is sink} then
3. Among the eligible top-sub rings, choose the one with the largest
number of total (remaining) packets, say top-sub ring i
4. Schedule link (root(i),s) respecting interfering constraint
5. else
6. if {node.buffer == empty} then
7. Choose a random child c of node whose buffer is full
8. Schedule link (c, node) respecting interfering constraint
9. c.buffer = empty
10. node.buffer = full
11. end if
12. end if

V. 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

A. *Multi-Channel Scheduling*

Multi-channel communication is an efficient method to eliminate interference by enabling concurrent transmissions over different frequencies. 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 convergecast. These methods consider the channel assignment problem at different levels: the link level (JFTSS), node level (RBCA)

a) 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

b) Receiver-Based Channel Assignment (RBCA)

Every node in the rings, 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

VI. IMPACT OF ROUTING RINGS

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.

The ring works in an efficient manner either in clockwise or anticlockwise direction A failure in node breaks the loop and can take down the entire network. but congestion of traffic and double path communication.

VII. EVALUATION

In this section, we evaluate the impact of transmission power control, multiple channels, and routing ring on the scheduling performance for both aggregated and raw-data convergecast.

We deploy nodes randomly in a region whose dimensions are varied between 15 × 15 m^2 and 150 × 150 m^2

A. *Impact of Transmission Power Control*

We investigated two cases: (i) when nodes transmit at maximum power, and (ii) when nodes adjust their trans-mission power according to the algorithm described. In both cases, nodes communicate on the same channel and use minimum-hop routing rings.

In the first case, time slots are assigned according to BFS-TIMESLOTASSIGNMENT for aggregated data, and according to LOCAL-TIMESLOTASSIGNMENT for raw data

B. *Impact of routing ring*

In the preceding sections, we observed that although interference can be substantially eliminated by using power control and multiple channels, connectivity of the ring still limits the performance

C. *Impact of Interference*

In this section, for the different channel assignment methods, we evaluated the required number of channels to completely eliminate interference as a function of deployment density

VIII. CONCLUSIONS

In this paper, we studied fast convergecast in WSN where nodes communicate using a TDMA protocol to minimize the schedule length. We addressed the fundamental limitations due to interference We also observed that node-based (RBCA) and link-based (JFTSS) channel assignment schemes are more efficient in terms of eliminating interference

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