Efficient Distributed Medium Access Arbitration for Multi-Channel Wireless Sensor Networks

Mohamed Younis and Samuel Bushra
Dept. of Computer Science and Electrical Engineering
University of Maryland Baltimore County
younis, sbushr2@cs.umbc.edu

Abstract — **Wireless sensor networks can be employed in a wide range of applications such as disaster management, combat field surveillance and homeland security. Sensors in such applications are deployed in mass and are usually constrained in the amount of available onboard energy. This paper presents ARCH, a distributed medium access Arbitration of multi-Radio-CHannel based sensor networks. ARCH is an energy efficient, scalable and collision free MAC layer protocol that combines frequency and time division principles for medium sharing. To achieve scalability sensors are partitioned into cells. One of the sensors in a cell is designated as a cell-head. ARCH employs a distributed algorithm for arbitrating channels among cells to enable simultaneous non-interfering data collection. Intra-cell transmissions are scheduled by the cell-head using the assigned channel. Cell-heads aggregate the gathered data and forward it over inter-cell-head paths to the base-station. The base-station assigns distinct channels to the independent branches of the inter-cell routing tree. Data transmission and reception on a branch is further scheduled in depth-first ordering. ARCH allows nodes to stay in the sleep mode for the longest duration and avoids collisions and thus it minimizes energy consumption and boosts the robustness of the network operation. The performance of ARCH is validated through simulation.**

I. INTRODUCTION

Interest in applications of wireless sensor networks (WSNs) has grown significantly over the past few years [1]. Examples of these applications include forest monitoring, border protection, and battlefield surveillance, where WSNs are to be deployed in remote and inhospitable environments to collect useful information without a human risk. It is envisioned that WSNs will consist of hundreds of miniaturized sensor nodes that operate on small batteries. Since a sensor becomes dysfunctional when it runs out of energy, a WSN may be structurally damaged if many sensors exhaust their onboard energy supply. In addition, WSNs are expected to be formed in the field in an ad-hoc manner. Due to the lack of infrastructure and the uncertainty about the inter-node communication links the network is usually bootstrapped and managed through coordination among the deployed nodes. Network management in this context refers to the establishment of data paths and the arbitration of medium access.

The large scale, the energy-constrained and the ad-hoc nature of WSNs have motivated lots of research on the effective and efficient design and management of such networks. To support scalability, partitioning nodes into clusters and the pursuance of distributed algorithms have been endorsed by the research community. Meanwhile, energy conservation has been exploited at many levels, e.g. power-down modes, programmable transmission ranges, multi-hop routing, etc. In most cases, energy conservation comes at the price of increased data collection delay. For example, activating a subset of the deployed nodes and forwarding data on least energy-cost paths often increase the number of hops and thus lengthen the packet delivery latency. Increased delay can slow down reaction to serious events and is thus undesirable. In this paper we strive to support the scalability, energy efficiency and responsiveness goals at the MAC layer.

We consider a two-tier network architecture in which nodes are grouped into cells using a distributed clustering algorithm. Each cell has a head node that collects the readings of the sensors in the cell. The cell head (CH), which is a regular sensor node, performs data aggregation and routes the cell report to the base-station over an inter-CH multi-hop path. The cluster algorithm parameters are adjusted to yield a connected inter-CH topology. Routes from cell heads to the base-station are also established in a distributed manner. While cluster formation and route setup in the considered architecture are based on previously published techniques, we pursue a novel protocol, called ARCH; for distributed medium access Arbitration of multi-Radio-CHannel based sensor networks.

ARCH enables efficient usage of the available bandwidth through the careful assignment and spatial reuse of radio channels. ARCH strives to achieve collision-free nodes' transmissions through scheduling the medium access on the available frequency bands (channels). Cell heads arbitrate the use of channels among themselves in order to avoid inter-cell interference. We present a novel distributed channel assignment algorithm that prevents a cell from picking any of the channels selected by the neighboring cells. A CH will then use the selected channel to assign distinct time slots to the nodes in its cell. The time-based intra-cell medium access arbitration will allow nodes to avoid wasting their energy in idle listening and transmission retries.

The same medium sharing principle is further exploited for inter-CH communication. Different channels are assigned to non-intersecting data paths, i.e. independent branches of the routing tree. Packet transmissions on the same branch are scheduled in a depth-first ordering to allow successive data aggregation. Thus, the inter-CH communication along most routing paths can also be performed simultaneously and without collisions. Overall, the non-interfering channel use boosts robustness of the inter-node links and minimizes packet drops. In addition, the increased simultaneity of transmissions lowers data collection latency and thus boosts the network responsiveness. The distributed nature of medium access arbitration combined with the tiered network structure make ARCH scalable for large network sizes.

The paper is organized as follows. The next section describes the architectural and operational models of the considered WSN. Section III contrasts ARCH with related schemes in the literature. Section IV provides a detailed description of ARCH. In section V, the performance of ARCH is studied through simulation. Section VI concludes the paper.

II. THE ARCHITECTURAL AND OPERATIONAL MODEL

A set of stationary sensors is randomly spread throughout an area of interest. A sensor is battery-operated and equipped with a limited data processing engine and a radio. Each sensor is assigned a unique ID prior to deployment. Sensors group themselves into disjoint cells by applying a distributed randomized clustering algorithm such as HEED [2]. The basic idea is for a small percentage of sensors to assume the role of cell-heads (CHs) and start recruiting neighboring nodes for joining their cells. The clustering process ensures that each node is mapped to exactly one cell and that the node can directly communicate with its CH. It has been shown that for a given sensor's transmission range, the probability of CH selection can be adjusted to ensure inter-CH connectivity [2].

Typical operation of the network involves the collection of data from individual sensors to their respective CHs, in what is called the *intra-cell* phase. The CHs are spared from any sensing activities to alleviate their load and energy consumption. Upon receiving data from its cell members, a CH performs data aggregation and then forwards the aggregated values to a base-station (BS) over an inter-CH dissemination tree (Figure 1). The latter is called the *inter-cell* phase. The inter-CH routing tree is a minimum spanning tree rooted at the BS and is formed in a distributed manner. The diameter of the tree is further constrained to make it balanced. The One-Time Tree Construction algorithm proposed in [3] can be used for that purpose. Balancing the routing tree will leverage ARCH, as will explain later, and shorten the data collection delay.

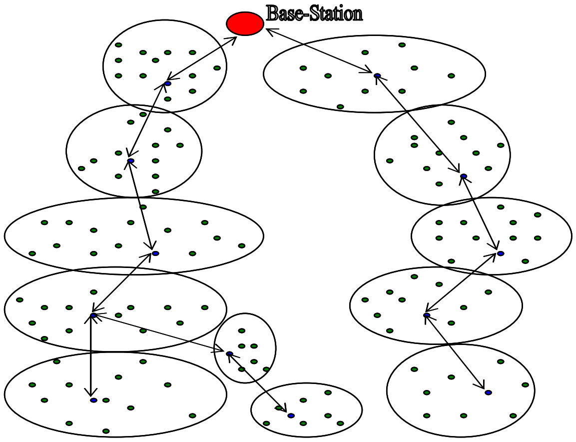

Figure 1: Inter-cell-head routing tree is formed to collect data to the base-station.

A sensor is assumed to be capable of operating in active or a low-power stand-by mode. The radio and processing circuits can be powered on and off. In addition the transmission power can be programmed based on the required range. The radio onboard a sensor node is capable of transmitting and receiving on multiple channels; tuning into a single channel at a time with no simultaneity among the transmission and reception. Meanwhile, the BS is significantly less constrained in energy and computational resources than sensors. It is assumed that the BS has multiple radio transceivers tuned to distinct frequency channels so that it can simultaneously receive data packets from multiple sensor nodes, i.e. CHs. The BS has enough transmission power to reach all sensors in the network.

III. RELATED WORK

MAC protocols proposed for WSNs can be classified into centralized, e.g. [4][5], with the BS scheduling medium access and distributed, such as [6], where nodes coordinate among themselves. Some employ a single channel [4][6]; others use multiple channels [5][7]. While some apply contention-based schemes [7]; others use reservation-based ones [4][5][6]. Most of the proposed MAC protocols are also geared for optimizing power consumption. A survey can be found in [8].

Prior work on multi-channel MAC in MANET usually pursues channel reservation and can be classified according to the employed reservation mechanism into three groups; two-round reservation [5][9], using dedicated control channel [7][10] and receiver-based reservation [11]. Most of these protocols do not study optimal channel arbitration among links. Our approach pursues distributed channel arbitration rather than a per-connection or per-link reservation. We take advantage of the static nature of sensor nodes to avoid the per-channel group membership maintenance that is often necessary in MANET. In addition, we exploit channel diversity at the network layer to further increase simultaneous channel use.

Like ARCH, SMACS employs a hybrid TDMA and FDMA medium sharing scheme [6]. Sensors agree with their neighbors on a schedule for medium access. The interference between adjacent links is avoided by randomly assigning different channels to potentially interfering links with FDMA. A flat network topology is assumed. ARCH employs a distributed channel allocation algorithm to make sure that neighboring cells use unique channels. Therefore, ARCH would achieve better utilization of the available bandwidth and minimize interference throughout the network. In addition, frames in SMACS tend to be large causing increased latency.

On the other hand, PARMAC considers a tiered network topology [12]. Similar to ARCH, intra-cell communication is based on time-based medium sharing. Inter-cell collisions are avoided by assigning distinct slots to every cell. Other work, like [4] and [13], also tried to address the potential of inter-cell collisions by changing the slots assigned to conflicting transmissions in neighboring cells. However, these approaches often yield large frame sizes; leading to an unacceptable increase in data latency. ARCH efficiently addresses the inter-cell interference through careful channel assignment.

IV. DISTRIBUTED MEDIUM ACCESS ARBITRATION

Generally, an efficient MAC layer protocol for WSNs should have the following design attributes:

- The protocol should be scalable since most applications of sensor networks involve a large set of sensor nodes.
- Collisions among the transmissions of various nodes should be avoided. Collisions lead to packet drop and thus reduce throughput and cause energy wastage.
- Idle mode of operation and transmission overhearing among sensors waste energy and thus should be minimized.
- The protocol should not be contention-based. Control packets overhead and active sensing of the medium, typically performed by contention-based protocols, are inefficient in terms of energy consumption. In addition, the data collection latency tends to be unpredictable in such case.
- Given the resource constraints, the protocol should impose little overhead on the communicating nodes.

ARCH exploits the availability of multiple radio channels in order to achieve the above efficiency goals. It pursues a hybrid time and frequency based medium sharing mechanism and it leverages the routing and clustering mechanisms mentioned earlier. ARCH serves both the intra and inter-cell communication phases. Generally ARCH arbitrates the use of radio channels in order to prevent interference and to increase simultaneity of medium access. When nodes are allocated the same channel, ARCH enforces a time based medium sharing among them. In the rest of this section, we describe ARCH in details.

A. Distributed Channel Arbitration

CHs collect data reports from sensors in their clusters and aggregate them before sending to the BS. When using a single radio channel, a CH can suffer collisions if multiple sensors in its cell transmit their packets at the same time. The same applies across cells too. A sensor's transmission in one cell can coincide with that of a sensor in a neighboring cell causing a hidden terminal problem. To prevent intra-cell collisions, we pursue a time-based arbitration of medium access. Intra-cell operation is coordinated by the CH. As we later elaborate, a TDMA frame is established and each sensor is assigned a time slot for transmission. After a sensor sends its data, it switches to a sleep mode until its assigned slot comes up in the next round. The transmission period, i.e. frame size, is known as the *intra-cell communication phase*.

While the same scheme can be applied to avoid inter-cell interference by establishing a global ordering of all cells, we opt to increase the simultaneity of the medium access in order to lower the data delivery latency. To do so, CHs arbitrate the available channels among themselves so that distinct channels are assigned to neighboring cells. We employ a novel distributed channel assignment algorithm to allow CHs to resolve potential conflicts with other cells. Basically, each CH picks a channel at random and forms a list of cells that are in its range (neighbors). Those neighbors can be known at the conclusion of the clustering process. Recall that inter-CH connectivity can be ensured by appropriately selecting the probability of a node to be a CH [2]. A CH_i then waits for all its neighbors with higher IDs to announce their channels. When its turn comes, CH_i ensures that it picks a non-interfering channel that is unused by the preceding neighbors on the list. Such a protocol maximizes channel reuse and thus minimizes the necessary number of distinct frequency bands. The algorithm is outlined in Figure 2.

```
CH_i pick s a channel $\Phi_i$ and form set $Neighbors(CH_i)$
Sort $Neighbors(CH_i)$ according to node ID
$j = 1$, // point to the top of $Neighbors(CH_i)$
While $ID_i < ID_{Neighbors(j)}$ and $j <= | Neighbors(CH_i)|$ do
    Wait until receiving $\Phi_{Neighbors(j)}$
if $(\Phi_i \neq \Phi_{Neighbors(k)} \forall k \leq j)$ then
    Broadcast $(ID_i, \Phi_i)$
else
    Select an unused channel $\Phi$
Broadcast $(ID_i, \Phi_i)$
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Figure 2: Pseudo code for ARCH's distributed channel assignment algorithm

ARCH's distributed channel assignment algorithm introduces very little message overhead. All message exchange takes place among neighbors. Every CH will broadcast only one message to announce its channel Φ. Therefore, the message overhead is linear in "N"; the number of CH. In addition, each node would only wait for its neighbors. Assuming a maximum node degree of d in the inter-CH network, each CH waits for at most d other CHs, which will speed up the channel selection process (In the worst case, d becomes N if a CH has links to all other CHs). We next prove the correctness and convergence properties of the channel assignment algorithm.

Theorem 1: In ARCH, the channel selection by the individual CHs is not conflicting.

Proof: According to ARCH, picking a new channel Φ_i of CH_i implies that all neighbors of CH_i will not simultaneously change their selected channel till CH_i broadcasts Φ_i. Those neighbors with higher IDs than ID_i should have already picked their channels and CH_i picks a channel Φ_i that is different from them. Neighbors, which have lower IDs than ID_i, will wait to know Φ_i before adjusting their channel selection. Non-neighboring CHs do not interfere with CH_i. □

Theorem 2: The channel selection is guaranteed to terminate in a maximum of N iterations, where N is the number of CHs.

Proof: After CH_i determines its order among its neighbors, CH_i either adjusts its channel selection or waits for the neighbors that have higher IDs. If CH_i has the least ID and is connected to all CHs, it will be able to finalize its channel selection after all the other (N-1) CHs take their turns. □

From Theorem 2, the upper bound on the required number of channels for this phase equals to one plus the highest node degree in the network, which happens when the node of the highest degree is also a CH. The frequency channel Φ_i that is picked by CH_i is used for data collection in the cell. Each sensor in a cell is arbitrarily allocated a time slot for sending its data. The CH_i tunes its radio to that channel during the intra-cell phase. Since simultaneous transmissions can happen in neighboring cells without collisions, there is no need for a large frame size to accommodate all the cells in the network. The frame size is determined by the cell, which has the maximum number of sensors. After the routing tree is formed, each CH shares its cell information with the BS, which can later on inform all the CHs about the largest number of slots needed for intra-cell communication. This way, the CH, whose cells only have a few sensors, can sleep until the start of the inter-cell communication period.

B. Inter-cell communication phase

After aggregating the sensor readings in its cell, a CH forwards the data report to the BS over an inter-CH path. As discussed in section II, a routing tree for CHs is formed in a distributed manner. Given the involvement of multiple CHs in reaching the BS, a CH cannot use the channel that is locally used in its cell. In other words, communicating CHs have to agree on a distinct radio channel. Two options for channel selection are applicable for enabling inter-CH communication. The first is to designate a radio channel for sole use by CHs in routing data to the BS. Arbitrating the CH transmission on that channel would be through either CSMA or TDMA discipline. The drawback in that approach is mainly the delay, which can be even unpredictable if CSMA is pursued.

The second option, which we adopt, is to utilize multiple channels for the inter-CH communication phase. We strive to establish a balanced routing tree. As mentioned in section II, we employ an algorithm, e.g. [3], to form a constrained diameter spanning tree for all CHs. Such an approach results in a tree of multiple independent, i.e. non-intersecting, branches with constrained depth. To expedite the data forwarding from CHs, a distinct channel is used on the individual independent branches. The BS can easily do the channel assignment in this phase given that it is the target node for transmissions on all branches, i.e. the sink node for the network. The BS is not resource constrained and is assumed to have mulitple radio transceivers for simultaneous recepition on multiple channels. Medium arbitration among the CHs on the same branch is time-based. Given that data aggregation is performed incrementally at each CH along the path, depth-first ordering is pursued for assigning time slots. Thus, the maximum latency for that phase is proportional to the maximum depth of the inter-CH routing tree. The duration required per data collection round is the combined frame for intra and inter-cell phases.

C. Detailed Illustrative Example

To put it together, we now show a detailed illustrative example for how ARCH works. Figure 3 shows an example of a network upon the conclusion of clustering process and the formation of the routing tree. The arrows represent the inter-CH paths. Lines between CHs indicate connectivity.

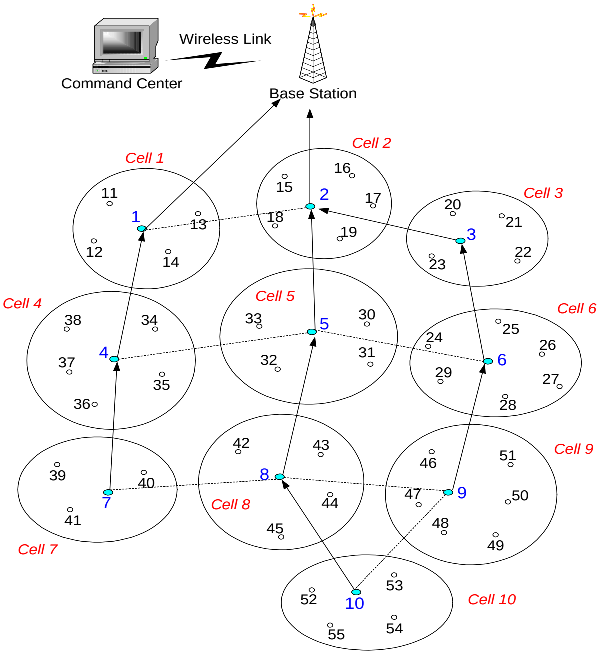

Figure 3: The architecture of an example network

In the example, the network consists of 55 sensors that get grouped into 10 cells. A simple numbering scheme is used for node ID, which is annotated next to each sensor. Since node 5 and 8 each has 4 neighbors, five radio channels are required for ARCH. Each CH node randomly picks a channel out of these 5 channels. Assume that the picked channels are as in Table 1. There are channel conflicts between nodes 1 and 4 and between nodes 5 and 8. The following summarizes the various iterations till ARCH eventually converges to a collision free channel assignment and medium access schedule:

Table 1: Initial channel selection for the 10 cells

Node ID	1	2	3	4	5	6	7	8	9	10
Channel	2	3	2	2	1	4	4	1	3	5

1. Node 10 broadcasts that it picked channel 5. The other CHs do not have the highest ID among their respective neighbors.
2. Node 9 does not conflict with node 10 and broadcasts that it picked channel 3. No other node is ready to go forward.
3. Nodes 6 and 8 are ready to check their channel selection. Node 8 picked channel 1 and thus does not interfere with nodes 9 and 10. Node 6 selection of channel 4 does not conflict with node 9. Thus, nodes 6 and 8 broadcast their choices. Nodes 1, 2, 3, 5 and 7 keep on waiting.
4. Nodes 3, 5 and 7 have the highest IDs among their unready neighbors. Node 7 has no conflict with 8's selection and the same applies for nodes 3 and 6. Node 5 may interfere with node 8 and thus picks a different channel that does not also conflict with node 6. Let us assume that it selects channel 3. Each of nodes 3, 5 and 7 broadcasts its channel number.

5. Nodes 2 and 4 can proceed. Node 4 selection of channel 2 does not conflict with nodes 5 and 7 and thus can be announced. Node 2 finds a conflict with node 5, which currently rely on the use of channel 3 (iteration 4). Node 2 then picks channel 5 to differ from nodes 5 and 7.
6. Node 1 is the only one left in the network. It has a conflict with node 4. It thus switches to channel 4.

Table 2: ARCH based channel assignment for the 10 cells

Node ID	1	2	3	4	5	6	7	8	9	10
Channel	4	5	2	2	3	4	4	1	3	5

In this example, the channel arbitration algorithm converges in 6 iterations. Table 2 shows the final channel assignment, which is conflict free. Since simultaneous intra-cell communication can now take place, CHs assign specific time slots to sensors in their cells. Table 3 shows the intra-cell frame in which all channels have overlapping transmissions. For the inter-cell communication, slots are assigned in a depth-first (Table 4). Two channels are picked since there are only two independent branches in the routing tree. Channels 1 and 2 could be reused since the inter-cell phase does not overlap with the intra-cell one. Data from cell 7 is further aggeragted at node 4 and forwarded to node 1, which will do the same before reporting to the BS. The same applies to the second branch.

Table 3: Intra-cell frame and slot assignment for all channels

Channel 1	42	43	44	45		
Channel 2	20	21	22	23		
	34	35	36	37	38	
Channel 3	30	31	32	33		
	46	47	48	49	50	51
Channel 4	11	12	13	14		
	24	25	26	27	28	29
	39	40	41			
Channel 5	15	16	17	18	19	
	52	53	54	55		

Table 4: Slot allocation for the inter-cell phase

Channel 1	7	4	1				
Channel 2	10	9	8	5	6	3	2

V. EXPERIMENTAL VALIDATION

In this section, we discuss the validation of ARCH through simulation. Section A describes the experiments and defines the performance metrics. In section B, the results are analyzed.

A. Experiment Setup and Performance Metrics

The simulator implements the clustered network model, discussed in section II, using Microsoft Visual C++. In the experiments, a set of sensors is randomly placed in a 400m x 400m area. The BS is randomly positioned within the boundaries of the deployment region. The range of a sensor is assumed to be 50m, and it can be increased to a maximum of 100m. The communication range of the BS is assumed to cover the whole deployment region. The range of a CH is set to about 1.5 times the range of a normal sensor to ensure connectivity with other CHs. We set the initial percentage of CHs to 5 % of the node population. We have studied ARCH's performance under numerous metrics, e.g. delay, throughput and energy. However, due to space constraints, we report only on the following subset, which captures scalability and latency:

- Average number of neighboring cells with same channel: This metric is used to measure the level of conflicts (and eventually interference) caused by the selection of the same channel in neighboring cells. ARCH is compared to random selection of channels for *intra-cell* communication.
- Channel Allocation algorithm convergence rate: The convergence rate represents the average number of iterations needed so that all cells and their neighbors pick distinct channels for transmissions.
- TDMA frame size: Small frames allow the effective handling of high data rates. ARCH allows for overlapping of transmissions among neighboring cells. This metric captures the effect of transmission overlap on reducing the *intra-cell* and *inter-cell* frame size.

B. Simulation Results

In each experiment, we varied the number of deployed sensors between 100 and 800 sensors. Experiments were run for several network topologies, generated through different seed values, until the results approximately reached the 90% confidence level while staying within 8% of the sample mean.

Inter-cell Interference: Figure 4 shows the average number of cells that are neighbors and use the same channel. As expected, when the number of sensors increases, the network becomes denser and cells tend to have more neighbors. When channels are randomly allocated, it is more likely to assign a channel to one cell that is similar to some of its neighbors causing a rapid increase in inter-cell conflicts. Meanwhile, ARCH always terminates when all neighboring CHs choose distinct channels.

Convergence rate: Figure 5 shows the average number of iterations taken by the channel allocation algorithm. As the number of sensors increases, the average number of iterations slightly grows from 5 for 100 sensors to 8 for 800 sensors. This shows that even if there are many sensors in the network, the algorithm goes through only a few iterations before it successfully terminates. The number of iterations is compared against the number of cells in the network to determine the algorithm's scalability. Recall that in the worst case the algorithm takes the number of iterations to be equal to the number of cells. The experiments indicate that the number of iterations does not increase linearly with the number of cells. This shows that the algorithm is scalable for large networks.

TDMA Frame Size: Figure 6 shows the frame size generated by ARCH. As the number of sensors increases, the number of slots per intra-cell frame stabilizes around 22. This is because:

- Large networks tend to have many cells with a small number of sensors.

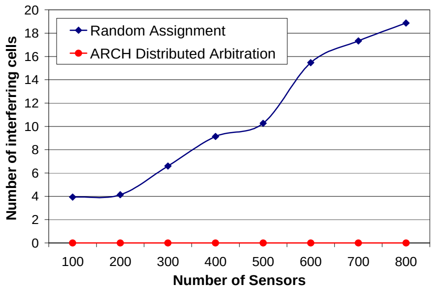

Figure 4: Average number of neighboring cells that use same channel

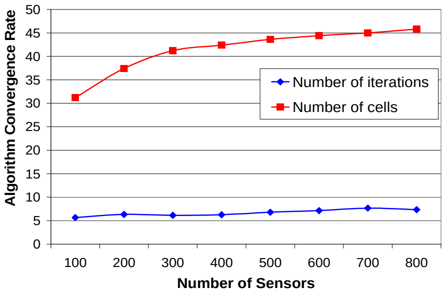

Figure 5: No of iterations for the ARCH's channel arbitration algorithm to converge

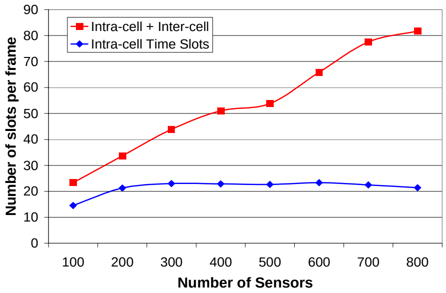

Figure 6: Intra-cell and Inter-cell communication phase frame sizes

- Since neighboring cells use different channels during the *intra-cell* communication phase, sensors in different cells can use the same time slot without any signal interference.

It is worth noting how the number of slots needed for *intra-cell* phase almost stays constant compared to the total number of slots needed for the combined intra and inter-cell phases.

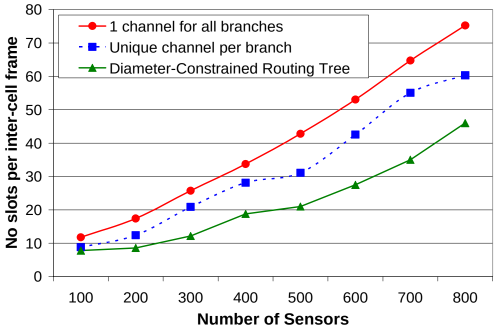

Figure 7: Inter-cell frame size with and without ARCH

Figure 7 shows the frame size yielded by ARCH for the inter-cell communication phase. The top 2 curves use the well-known Prim's algorithm for constructing the routing tree; one uses just one channel across the routing tree, while the other uses a unique channel per branch. The bottom curve uses the diameter-constrained routing tree algorithm [3]. As expected, the diameter-constrained tree case uses fewer time slots, since it attempts to constrain the diameter of all branches.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented ARCH; a novel MAC protocol for multi-channel WSNs. We considered a network architecture in which nodes are grouped into cells; each is led by one of its member sensors (cell-head). Data collected from sensors to their respective cell-heads and then forwarded over inter-cell-head paths to the base-station. ARCH enables the efficient usage of the available bandwidth through the careful assignment and spatial reuse of radio channels. ARCH pursues a combined FDMA and TDMA scheme in order to limit data collection latency and avoid interference among nodes' transmissions. ARCH employs a distributed algorithm to arbitrate channels among cells. Distinct channels are also assigned to the different routing branches in order to expedite the data delivery to the base-station.

ARCH is validated through simulation. The performance results have demonstrated that even with high sensor densities, ARCH's distributed channel allocation algorithm converges after only a few iterations. ARCH allows for overlapping of transmissions among neighboring cells without collisions. This results in small frame sizes, which allow for the effective handling of high data rates. We have also shown that the frame size for inter-cell communication can be further reduced when the diameter of the routing tree is constrained.

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