Reducing Inter-cluster TDMA Interference by Adaptive MAC Allocation in Sensor Networks

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Abstract

This paper presents a Self-Reorganizing Slot Allocation (SRSA) mechanism for TDMA based Medium Access Control (MAC) in multi-cluster sensor networks. The aim is to provide a MAC layer protocol that can reduce inter-cluster TDMA interference without having to use spectrum expensive and complex wideband mechanisms such as CDMA or FDMA. The primary contribution of this paper is to demonstrate that with adaptive slot allocation, it is possible to reduce inter-cluster interference under low loading conditions. The second contribution is to design a feedback based adaptive allocation reorganization protocol that can significantly reduce the inter-cluster interferences without relying on any global synchronization mechanisms. We present the design of SRSA and provide a simulation based characterization of the protocol in comparison with TDMA-over-CDMA, TDMA with random slot allocation and CSMA MAC protocols.

1. Introduction

Sensor networks typically consist of very large number of low cost sensor nodes which collaborate among each other to enable a wide range of applications. Unlike traditional data networks, communication protocol design in sensor networks is influenced greatly by their limited energy supply. Therefore, it is crucial for the sensor network protocols to be energy efficient in order to extend network lifetime. Traditional wireless MAC protocols such as IEEE 802.11 are designed for optimizing throughput, latency, and fairness without specifically concentrating on their energy usage. The asynchronous nature of these protocols prevents energy savings by not allowing wireless nodes to selectively put their network interfaces into low-energy sleep modes [1]. In this paper we present an energy efficient MAC protocol, Self-Reorganizing Slot Allocation (SRSA), for implementing spatial TDMA in multi-cluster sensor networks.

In a multi-access MAC, the non-essential energy expenditures are contributed [1] by the following four sources. (1) protocol overhead; (2) packet collisions; (3) overhearing; (4) idle listening. Previous research has shown [1, 5] that idle listening accounts for most of the energy consumption at low traffic situations, which are prevalent for lot of sensor applications.

A significant amount of work has been done [1,2,3,5,9] on reducing idle listening by powering off network interfaces when possible. The main goal is to operate at the smallest duty cycle while being able to support application loading requirements. A notable example of periodic active-sleep design is S-MAC [1], in which nodes synchronize in active-sleep cycles. By decreasing the active-sleep duty cycle, this protocol can trade energy for latency and effective channel bandwidth. A notable shortcoming of SMAC is that since the basic medium access mechanism is contention-based, due to channel contention it cannot have very small duty cycle and guarantied bounded delivery latency.

An alternative approach to periodic active-sleep cycles is the wake-up radio [5], in which a node normally sleeps, but when it has data to transmit, it first sends *wakeup* signal through another channel to wake up the receiver node. Since the only function of the radio for wake-up channel is to wake up sleeping nodes, the hardware for that interface can be simpler and less energy hungry. Nevertheless, this design adds an extra transceiver which is an added cost and complexity burden for low-cost sensor nodes.

While these contention–based protocols work well under low traffic loads, they degrade drastically under higher loads because of collisions and subsequent retransmissions. TDMA MAC protocols have built-in active-sleep duty cycles that can be leveraged for limiting idle listening, thus have better energy efficiency. Although this makes TDMA a natural choice for sensor MAC, successful implementation would require some form of spatial TDMA [4] in the presence of overlapping MAC clustering [2,3]. In such deployments, the main challenge is to devise TDMA slot allocation mechanisms with the goal of reducing allocation interference across overlapping clusters. A straightforward solution [2,3] to this problem is to use Code Division Multiple Access (CDMA) or Frequency Division Multiple Access (FDMA) across clusters and then to run independent TDMA schedules within each cluster. However, using CDMA or FDMA incurs costs in terms of spectrum usage as well as network interface complexity.

In this paper, we propose a distributed Self-Reorganizing Slot Allocation (SRSA) protocol that operates at the cluster level and does not rely on any information beyond a cluster. The main idea is to initiate MAC operation with a random initial TDMA allocation and then, adaptively change the slot allocation schedule locally, based on feedback derived from collisions experienced by the local nodes within a cluster. Reliance only on the local information ensures the scalability of SRSA over very large networks.

2. Self-Reorganizing Slot Allocation (SRSA)

Design of SRSA is targeted to meet the following requirements. First, the slot allocation process should be adaptive, with collision detection as a feedback parameter. Second, the protocol has to operate locally without having to rely on any inter-cluster communication, synchronization and global timing information.

2.1 Network Model and Assumptions

In our network model (see Figure 1) data is sensed from a sensor field and delivered to monitoring applications through base stations. It is assumed that each sensor node can communicate directly with at least one base station. For scalability, however, the

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network is self-organized into multiple clusters. A cluster head acts like the data aggregator and gateway between the nodes within its cluster and the base stations. The energy advantage of this cluster model can be found in [3].

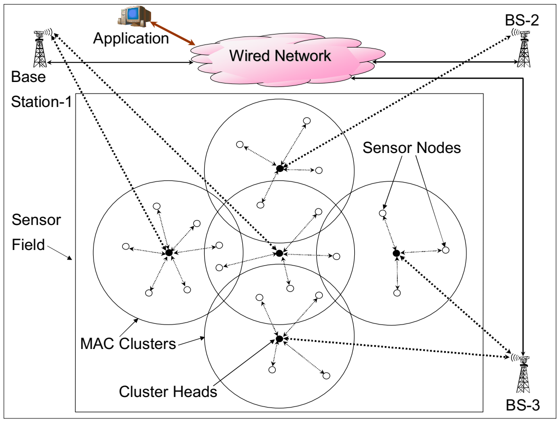

Figure 1: Sensor network and data flow model

Successful operation of this model would depend on three protocol components, namely, self-reorganizing cluster formation, autonomous cluster-head election and energy-efficient medium access control. This paper proposes a new MAC protocol while relying on the existing cluster formation protocols in [2,6,7,8] and cluster head election mechanisms in [2]. Note that in this paper we provide a MAC solution only for the intra-cluster communication. A separate mechanism will be necessary for the base station to cluster head communication. This mechanism is out of the scope of this work, and will be reported on a future publication.

2.2 SRSA Protocol Overview

After the clusters are self-organized and cluster heads are elected, each cluster maintains a local TDMA MAC frame. After a node receives its slot allocation, it remains active only during the allocated slots, and sleeps during all other slots for saving energy.

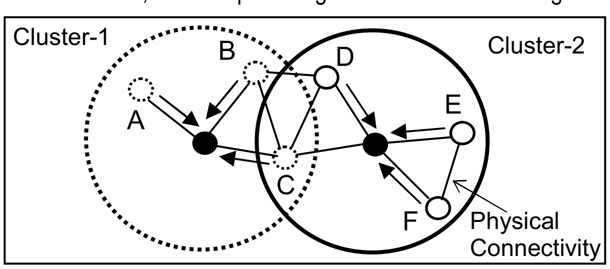

Figure 2: TDMA Collisions across overlapping clusters

In SRSA, we assume that the packets are of fixed size and the TDMA frame durations in all clusters are the same and pre-configured. However, the frame timing across the clusters is assumed to be asynchronous. All nodes within a cluster are time synchronized through their cluster-head. Data is exchanged only between a sensor node and its local cluster head. The baseline SRSA protocol is as follows.

Step-1 (Initialization): A cluster head initially makes a random TDMA slot allocation to its cluster nodes.

Step-2 (Carrier Sensing): Before transmitting, a node first senses the carrier to see if there is an ongoing transmission due to an overlapping allocation in any of the neighbor clusters. If the channel is found free then the packet is transmitted. Otherwise, a Carrier Sense Collision (CS-Collision) is declared and the packet is buffered until the next allocated slot for that node. A CS-collision indicates that there exists at least one overlapping allocation in one of the node's neighbor clusters. An example CS-collision situation will arise in the network in Figure 2 when node C in cluster-1 and node D in cluster-2 are allocated overlapping TDMA slots. Since C and D are within each others' transmission range, the node which starts transmission later will detect a CS-Collision.

Step-3 (CS-Collision Feedback): Upon detection of a CS-collision, a node sends that information to its cluster head through the next successful uplink packet transmission. A bit in the packet header is designated for carrying this information. This method of learning about a CS-collision by a cluster head is referred to as *active detection*. Another way to infer about a CS-Collision is by passive detection. If a cluster head observes that although uplink slots have been allocated, a node in the cluster is not transmitting uplink packets for a large number of frames, then a passive detection of CS-Collision takes place.

Step-4 (HN-Collision Detection): Consider a situation in Figure 2 when node C in cluster-1 and node E in cluster-2 are allocated overlapping TDMA slots. Since these two nodes are outside each others' transmission range, instead of CS-Collision, a Hidden Collision (HN-Collision) will occur at the head of cluster-2. Unlike CS-Collisions, the HN-Collisions cause packet drops and can be directly detected by the affected cluster heads.

Step-5 (Slot Allocation Reorganization): At the end of each TDMA frame, a cluster head examines all TDMA slots for CS-Collisions and HN-collisions. Then the cluster head executes a reorganization of the local slot allocation so that the number of CS and HN collisions can be reduced in subsequent TDMA frames, and eventually minimized in a stable range. The reorganized TDMA schedule is then downloaded by the cluster head to its cluster members at the beginning of the next frame.

A possible schedule download mechanism for a cluster head would be to broadcast a bitmap specifying the new slot allocation schedule. Depending on the size of the bitmap, it can be downloaded either as a part of the header of a downlink user packet or as a separate downlink control packet. Since all clusters work in a distributed and independent manner, missing or corrupted schedule download will still work; but with increased transient time for the protocol to reach a stable state.

Steps 3, 4 and 5 are iteratively executed to maintain stable and optimal allocation. Details of the allocation reorganization process (Step 5) and its impacts are described in the next few subsections.

2.3 Frame Scaling for Collision Reduction

To further reduce collisions in networks with nodes at cluster boundaries, we introduce the concept of *frame scaling*: the TDMA frame duration is scaled up so that there are more slots in a frame than traffic in a cluster. The ratio of the number of available slots in a frame and the amount of traffic (slots per frame) is called Scaling

Factor (SF). The motivation for frame scaling is to introduce unused free slots which can be utilized for alleviating both CS and HN collisions. With scaling factor 2, a collision free slot allocation for the network on Figure 2 is shown in Figure 3.

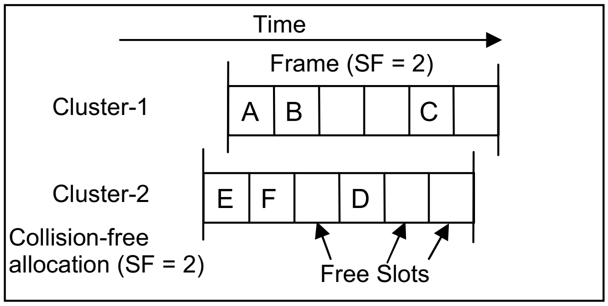

Figure 3: Use of frame scaling for collision reduction

Frame scaling has the following limitations. (1) by inserting free slots, the effective channel capacity is reduced. (2) with increased frame duration, the average packet delivery latency increases. Conceptually, frame scaling serves the same purpose as that of active-sleep cycles in SMAC [1]. The free slots in scaled frames extend the sleep duration of a node at the expense of lowering the allowable loading range. In effect, frame scaling decreases TDMA's inherent duty cycle by the factor SF.

2.4 Allocation Reorganization Algorithm

The following mechanism is used by a cluster head for allocation reorganization mentioned in Step 5 in Section 2.2.

Step-1: At the end of a frame, a cluster head examines all the slots and mark their status as one of F (Free), U (Uncontested: there was no collision detected for this slot), C (CS-Collision detected) and H (HN-Collision detected).

Step-2: For each H slot, the cluster head looks for an F slot and, if found, the H and F slots allocation are swapped.

Step-3: If for an H slot, an F slot is not found then the cluster head looks for a C slot and, if found, the H and C slots are swapped between the previously allocated nodes.

Step-4: If for an H slot, an F or a C slot is not found then the cluster head looks for a U slot and, if found, the H and U slots are swapped between the previously allocated nodes.

Step-5: For an un-swapped C slot, the cluster head looks for an F slot and, if found, the C and F slots are swapped between the previously allocated nodes.

Step-6: If for an un-swapped C slot, an F slot is not found then the cluster head looks for a U slot and, if found, the C and U slots are swapped between the previously allocated nodes.

These steps will execute iteratively till a stable allocation schedule is found. Note that the future allocation schedule for a given cluster depends only on its current schedule, current schedules of its neighbors, SF, and the traffic load.

3 Dimensioning Frame Scaling Factor

While reducing collisions, the tradeoffs for higher SF are increased latency and lower effective channel capacity. Therefore, it is necessary to appropriately dimension the value of SF so that it is not larger than what is needed for zero collisions at steady state.

For a network with given topology, its critical scaling factor $SF_{critical}$ is defined as the minimum SF at which there exists a zero-collision allocation combination across all the clusters. It turns out that finding the value of $SF_{critical}$ in an arbitrary network is NP hard. Therefore, in this paper we compute the bounds for this quantity.

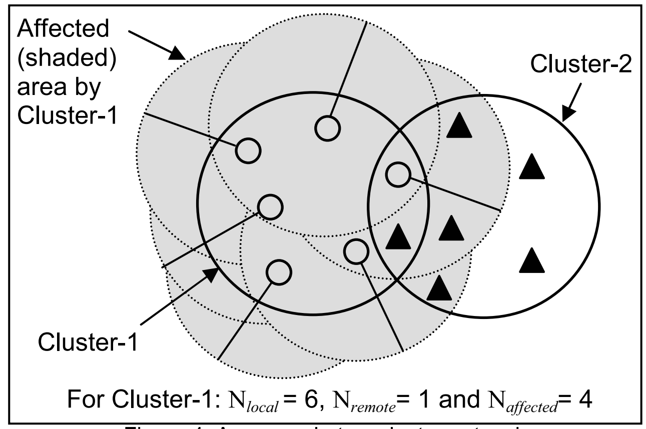

Figure 4: An example two-cluster network

For a given cluster, we define the following parameters. N_{local}: number of nodes that belong to the cluster; N_{remote}: number of nodes that belong to other clusters and are located within the overlapping region of this cluster; $N_{affected}$: number of nodes that belong to other clusters and are located within the transmission range of all nodes in given cluster. The defined quantities are illustrated in an example two-cluster network in Figure 4.

In the presence of cluster-overlapping, the minimum number of slots needed (for zero collisions) for a cluster cannot be less than (N_{local} + N_{remote}). Therefore, the lower-bound of $SF_{critical}$ can be computed as: $SF^{LB}_{critical} = (N_{local} + N_{remote} + 1) / N_{local}$. The additional slot in the numerator is necessary to accommodate the inter-cluster frame asynchrony, as illustrated in Figure 3. On the other hand, the minimum required slots for zero collisions do not need to exceed (N_{local} + $N_{affected}$). This corresponds to the upper-bound of $SF_{critical}$, which can be computed as: $SF^{UB}_{critical} = (N_{local} + N_{affected} + 1) / N_{local}$. Consider a network with M clusters. The bounds for $SF_{critical}$ in cluster-k can be represented as $SF^{LB}_{critical}(k)$ and $SF^{UB}_{critical}(k)$. Assuming equal frame size across clusters, the bounds of $SF_{critical}$ across the entire network are:

$$SF^{LB}_{critical}(Network) = \max_k (SF^{LB}_{critical}(k)) \quad k=1,2,3\ldots,M$$

$$SF^{UB}_{critical}(Network) = \max_k (SF^{UB}_{critical}(k)) \quad k=1,2,3\ldots,M$$

For the network in Figure 4, $SF^{LB}_{critical}(1), SF^{UB}_{critical}(1), SF^{LB}_{critical}(2)\ and\ SF^{UB}_{critical}(2)$ are computed to be 1.33, 1.83, 1.33 and 1.66 respectively. Therefore, the network-wide values of $SF^{LB}_{critical}$ and $SF^{UB}_{critical}$ are 1.33 and 1.83, which are the maximum over both the clusters. For this network we have found the required $SF_{critical}$ to be 1.33 (same as

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the value of $SF^{LB}_{critical}$). This was experimentally found from ideal allocation vectors which are established through a brute force search across the entire allocation space. To summarize, for SF > $SF_{critical}$, SRSA will converge to a stable state. The convergence speed depends on network topology, SF, and the traffic load.

4. Performance Evaluation

SRSA has been simulated using a C-based event-driven sensor network simulator and its performance have been compared with TDMA-over-CDMA (TDCD), TDMA with random allocation (TDRN), and un-slotted 1-persistent CSMA. CSMA is chosen to represent the asynchronous MAC protocols (such as 802.11) for which energy saving is not possible by intermittent interface sleep In TDRN, independent random slot allocations are done in each cluster. It can be viewed as SRSA without adaptive reorganization.

4.1 Experimental Parameters

We simulate a sensor field with 5 overlapping clusters as shown in Figure 1.Clusters have a radius of 50 m, the same as nodes' transmission range. Each cluster contains 20 randomly placed nodes, which communicate directly with the cluster head. The distance between adjacent cluster-heads is varied for studying the effects of cluster overlapping on SRSA performance. For this purpose, we define a parameter, Cluster Overlapping Factor (COF) as 1 – (distance between cluster heads) / (3 * transmission range). With COF = 1, all 5 clusters in Figure 1 totally overlap, and with COF = 0 (when the adjacent clusters are separated by three times node transmission range), there is no overlapping between any two adjacent clusters. Unless specified otherwise, we have chosen an inter-cluster distance of 70m, for which COF = 0.53 and the corresponding sensor field dimension is 240m x 240m.

Following the specification in [9], we choose a radio data rate of 25.6 Kbps and fixed packet size of 128 bits (5ms), which is also the TDMA slot size. Note that this packet duration includes packet data time and carrier sense duration. TDMA frame duration is chosen as D+N×SF, where D is the number of slots allocated for downlink transmissions, N is the number of nodes per cluster and SF is a chosen frame scaling factor. For all experiments we have chosen the value of D as 9. Unless specified otherwise, for all experiments we have chosen SF = 2 and N = 20.

4.2 Simulation Results

Throughput: Throughput for all four protocols with Scaling Factor (SF) = 2 and Cluster Overlapping Factor (COF) = 0.53 are shown in Figure 5. TDCD (TDMA-over-CDMA), being completely collision free, can sustain a maximum load of one packet per frame from each node. With 20 uplink and 1 downlink slots per frame, the frame duration is 105ms (21 x 5ms). So the maximum sustainable load is approximately 9.5 packets/node/sec. Note that TDCD is able to achieve this high throughput at the expense of wide-band operations (CDMA/FDMA) and high interface cost and complexity.

Although at steady state, the SRSA protocol does not face any collisions (see Figures 6:a and 6:b) its throughput saturates at a lower load (4.08 packets/node/sec) due to frame scaling. For TDRN, the frame size is exactly the same as SRSA, but TDRN saturates at a lower load (approximately 3.75 packets/node/sec) because of higher CS and HN collisions as shown in Figures 6.

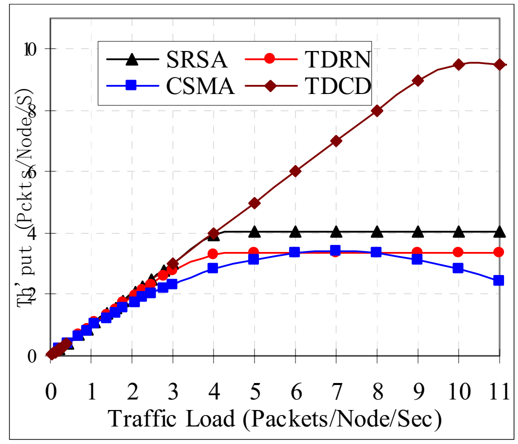
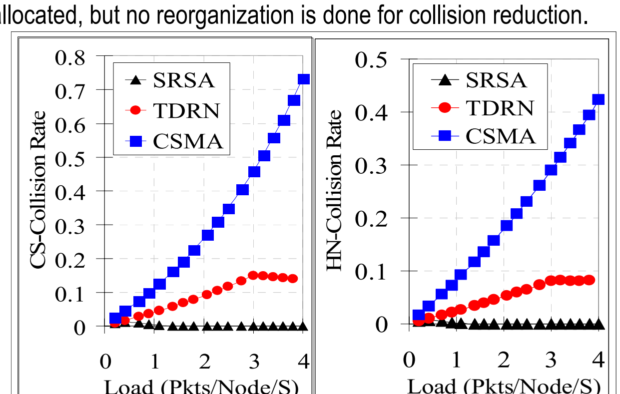


Figure 5: Throughput as a function of load

Collisions: CS-Collision rate is defined as the average number of transmission attempts aborted due to contented medium, normalized by the successful packet delivery count. HN-Collision rate is computed as the ratio of number of packet dropped due to hidden collisions to the successful delivered packet count. As shown in Figure 6, within the sustainable loading range, both the collisions are almost eliminated for SRSA. These results indicate the effectiveness of SRSA's feedback algorithm in the presence of frame scaling. The effects are particularly visible when contrasted with TDRN, in which frames are scaled and slots are randomly allocated, but no reorganization is done for collision reduction.



a) Impact of load on CS-Collisions b) Impact of load on packet drop

Figure 6: CS and HN collisions as a function of load

Latency: For all evaluated protocols in TDMA family (TDCD, SRSA and TDRN), the MAC latency has two components, namely, the queuing delay and a delay imposed by the TDMA framing itself. The latter is load independent and its average value is half the frame duration. CSMA does not have this frame-latency overhead. As a result, as shown in Figure 7, the latency for CSMA is the lowest (1.2 slots) among all four protocols at low traffic load.

On the other hand, TDCD, without scaling factor achieve lowest latency among TDMA protocols. Frame delay of SRSA is the same as that of TDRN. However, imposed queuing delay for TDRN is larger because of more CS-Collisions (see Figure 6) in the

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absence of allocation reorganization.

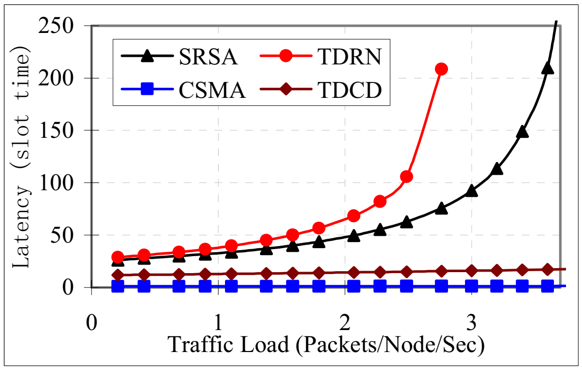

Figure 7: Packet delivery latency as a function of load

Energy Efficiency: Energy performance of all four protocols with varying inter-cluster distance is shown in Figure 8. For these experiments we chose a load of 1.38 packets/node/sec. Energy consumption for a protocol is represented by the average number of slots during which a node has to remain active for each successful packet delivery. For the inactive duration, nodes sleep to conserve energy. Larger node active times indicate higher energy consumption.

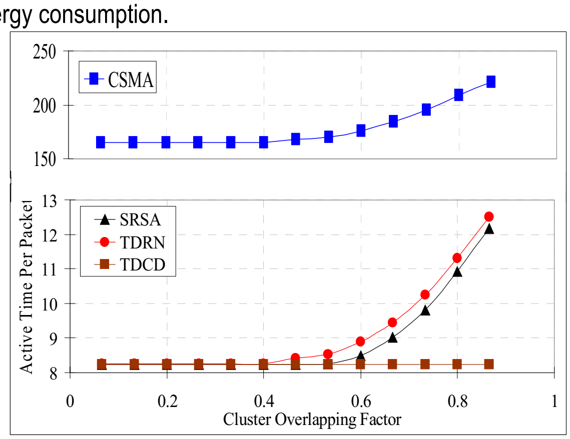

Figure 8: Energy expenditure as node active time

For all protocols except TDCD, the energy consumption increases with denser cluster placements. CSMA shows the worst energy performance because all nodes have to always remain active in order to receive asynchronous transmissions. For TDMA family of protocols, all nodes except the cluster heads have to be active only during their respective allocated slots only if there is a packet to transmit. Energy efficiency of TDMA based protocols is evident from their order of magnitude energy economy.

The energy drainage in TDCD is insensitive to cluster overlapping due to the absence of collisions. For SRSA and TDRN, both CS and HN collisions start increasing for larger COFs. In closely overlapped clusters, there are no optimal allocations by SRSA that can achieve zero CS and HN collisions. Energy dissipation due to these collisions accounts for the increase of node active time.

5. Conclusion and Future Work

We have presented a Self-Reorganizing Slot Allocation mechanism for TDMA based Medium Access Control in multi-cluster sensor networks. From the experimental results we conclude that the proposed SRSA protocol can achieve significantly better energy performance compared to the CSMA-type contention based protocols (see Tale 1). More notably, SRSA achieves this without having to incur the spectrum cost and interface complexity of the wideband MAC protocols such as CDMA. The trade-off for low energy dissipation and packet drop rate is increased packet latency, which is often tolerable for monitoring type sensor network applications.

	Narrow -band	Cost	Th'put	Packet Drops	Latency	Energ y
TD CD	No	High	High	Very Low	Medium	Low
SR SA	Yes	Low	Medium	Very Low	Medium.	Low
TD RN	Yes	Low	Medium	Medium	Medium.	Low
CS MA	Yes	Low	Medium	High	Low	High

Table 1: Overall performance summary

Future work on this topic includes analysis of inter-cluster TDMA interference and their impact on SRSA's convergence. Also, more experiments will be carried out to analyze the impact of frame scaling on SRSA's convergence performance.

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