Cluster-Centric Medium Access Control for WSNs in Structural Health Monitoring

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***Abstract*—Wireless sensor networks (WSNs) are designed for sensing phenomenon and acquiring data. In structural health monitoring (SHM) of critical infrastructure, increasingly large number of sensor nodes are deployed to acquire data at the spatial density needed for structural integrity assessment. After rare catastrophic events such as earthquakes, a large volume of data related to the event can be produced in an instant and need to be sent (to remote locations) for analysis. When many nodes are trying to transmit their data simultaneously, the contention for the wireless channel increases the probability of packet collisions resulting in packet drops, multiple retransmission attempts and consequently delays; it is also not uncommon to find certain nodes (e.g. closer to the sink) having better chances of successful transmission leading to biased data delivery. While clustering has been extensively used to reduce contention in wireless networks, researchers have not given adequate attention to cluster-level performance, preferring to focus on node-level performance. This paper presents a new perspective on cluster-based WSNs and proposes a cluster centric design that aims to tackle medium access control (MAC) layer congestion associated with burst packet generation in an unbiased manner, making it suitable for applications like SHM.**

***Index Terms*—Medium Access Control, Burst Traffic, Clustering, Network Bias / Unfairness, Structural Health Monitoring.**

I. INTRODUCTION

The emergence of wireless sensor networks (WSNs) can be traced back to an initiative by the National Research Council [1] and development has been motivated by military applications such as battlefield surveillance, where sensors are typically powered by batteries. Since then, new WSN applications, such as environmental monitoring and structural health monitoring (SHM) have emerged where deployment is expected to last much longer periods, and alternative energy sources like energy harvesting [2] are increasingly sought. Whether the sensor node is powered by batteries or energy harvesting, power constraint remains a key design issue. As the size of WSNs grow in response to real-world application needs, scalability also becomes an issue. A common approach to achieve the scalability is the adoption of a hierarchical network architecture and the use of clustering.

The many clustering approaches for WSN that appear in the literature have energy conservation as the primary focus [3]. The key functions of clustering in WSNs are cluster head selection, cluster formation and data transmission, all of which are concerned with the efficient operation of the network with little consideration of the application data requirements. Often, if not always, data packets are forwarded to cluster heads to be relayed to the sink. The various schemes are assessed from a node-centric perspective using traditional performance metrics like energy efficiency, packet delivery ratio, latency, as well as, the communication overheads of the clustering process.

In WSNs, packet delivery latency and network throughput requirements are usually relaxed in favour of reducing energy consumption. For this purpose, the IEEE802.15.4 standard [4] which is designed for low-rate wireless personal area networks (LR-WPANs) is a natural choice for WSNs that collect data over extended durations. Going back to the environmental monitoring example, sensors can be scheduled to operate with low duty cycles to minimize contention and save energy.

In recent years, the use of WSNs for structural health monitoring (SHM) has received significant attention from both the civil engineering as well as networking communities. SHM is used for detecting gradual deterioration of critical infrastructures over time due to corrosion, fatigue, scour, etc., and/or damage resulting from catastrophic events like earthquakes [5]. Civil engineers have used wired sensors to collect massive amounts of data that they require for structural integrity analysis. It is natural that they have the same expectations when using WSNs which unfortunately is not the case.

While the untethered feature of wireless communication alleviates the need for cables to connect sensors to the data acquisition centre, SHM applications tend to operate in environments that are harsh to wireless communication, e.g. presence of metal beams that interfere with the radio signals. That aside, contention-based MAC protocols (like IEEE802.15.4's Carrier Sense Multiple Access with Collisions Avoidance or CSMA/CA) that are extensively used in WSNs do not cope well with massive traffic burst [6].

A typical example can be a rare event such as the occurrence of an earthquake, all the sensors sense and report the event simultaneously. A massive burst of packets is generated containing critical data on structural vibration characteristics that need to be transmitted. This sudden influx of data into the network leads to severe network congestion, packet drops, delays, and repeated retransmission attempts.

To handle the high volumes of data while providing the necessary useful information required by civil engineers, clustering schemes resort to using in-network processing and aggre-

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gation/fusion of sensory data [7]–[10]. These schemes collect data at cluster heads and then attempt to reduce the number of duplicate/correlated data packets before transmitting the processed data. Performing in-network processing of SHM data requires in-depth domain knowledge to be integrated into the networking subsystem, which limits the use of the proposed schemes in other SHM scenarios. SHM data exhibit a high level of correlation and this has been successfully exploited for cluster formation, as previously noted.

For our work, we also exploit the clustering characteristic in the design of our medium access control (MAC) protocol whereby sensors that generate highly correlated data are grouped into a cluster. In practice, the clusters are defined by domain experts, e.g. structural engineers. Our proposed MAC protocol arbitrates access to the wireless channel in such a way that every cluster has a fair opportunity to transmit their data; this is achieved by viewing each cluster as a supernode. In this way, we are able to reduce contention and send the data quickly and fairly. Consequently, our approach is designed to provide civil and structural engineers the (raw) data that they need and at the same time address WSN constraints.

The rest of this paper is organized as follows. Section II gives a brief overview of some related work. Section III discusses the proposed cluster centric MAC scheme. Section IV compares and evaluates the performance of our protocol against standard IEEE802.15.4 CSMA/CA. Section V concludes the paper.

II. RELATED WORK

The related work on SHM with WSN is classified into two categories to reflect work : (i) motivated by information (generated by events) constraints, and (ii) motivated by network constraints in SHM applications.

A. It's all about the data

SHM applications exhibit certain key characteristics that traditional WSN algorithms and protocols have not been designed for, namely, the massive amounts of data needed by civil engineers for assessing the huge structures being monitored. This came about from the use of modal parameter estimation techniques that require large amounts of data collected from a dense array of sensors [11]. Such SHM systems have leveraged WSNs to collect raw sensor data with special considerations for bandwidth and energy constraints not present in the traditional wired systems; however, they still suffer from high energy consumption and large data delivery latencies.

As mentioned previously, the data produced by SHM systems are highly correlated in the space domain [12] which is a characteristic exploited by various node clustering algorithms (e.g. [7]–[10]). A simple cluster-based approach was proposed by Zimmerman *et al.* [7] using pre-defined two-node clusters where all nodes are within communication range of the AP. The study adopted output-only modal identification [11] to monitor the response characteristics of exciting a large civil structure in a controlled manner. The goal of the study was to demonstrate that distributed estimation techniques can be embedded within the wireless sensors to mitigate the data deluge. The limited scope of the study did not consider other topologies nor how to optimize the clustering to reduce energy consumption of WSNs. This motivated Liu *et al.* [8] to study how to optimally partition sensor nodes such that requirements from both modal analysis and WSNs (with regard to energy efficiency) are addressed. In their approach, the whole network is divided into single-hop clusters, each with a cluster head (CH) that performs analysis. They show that performing modal analysis at CHs and transmitting the processed bits takes up less energy, as compared to the traditional approach of sending all packets to the sink, even when the whole network is configured as a shortest path tree.

The work by Zimmerman *et al.* [7] was used by Jindal and Liu [9] to construct an optimal data forwarding and computing structure that minimizes energy consumption subject to a computational delay constraint. This study extends the earlier works by providing an efficient routing structure that is designed for distributed computation of SHM algorithms. Like [8], the algorithms were validated with simulations and testbed experimentation. Most of, if not all, the simulation results were based on 30 node topologies with node density of 8 nodes per m^2; for the experimental validation, 12 nodes were used as compared to the 10 node setup adopted in [8].

To further reduce the data dimensionality (and energy consumption), Hackmann *et al.* [10] proposed a flexible multi-level monitoring approach that incrementally activates sensors in damaged regions on demand, keeping most of the sensors asleep until they are needed. Under normal routine conditions, also known as first stage, a small number of sensors spread across the structure being monitored are enabled as a single cluster to perform damage identification; if no damage is detected, these sensors return to sleep. If damage is detected, additional sensors in the vicinity of the damage (i.e. detected by the first stage sensors) are activated to narrow down the region of damage. This process is repeated until the desired resolution for the damage location is achieved. Different sensors can be activated during different stages, as well as, during the same stage at different times. This enables load balancing among the sensors to extend the network lifetime.

In the WSN approaches motivated by information/data constraints (including those discussed above), the optimal structure (tree/cluster) needs to be pre-computed and cannot adapt to changing network conditions, e.g. fluctuating wireless link quality, nor deal with network traffic dynamics. Another potential problem is losing a single packet of processed data may render all information useless. WSN approaches motivated by network constraints [3], on the other hand, have been designed to address fluctuating network conditions with energy conservation as the primary aim while maintaining network connectivity but without explicit consideration for the quality of the data content.

B. It's all about the network

The IEEE802.15.4 MAC protocol is based on the standard CSMA/CA. It is simple and works well for low-rate low-power networks making it the natural choice of transmission method for WSNs. While this protocol works for light traffic (i.e. low-rate) its performance quickly degrades when network traffic increases, especially in the presence of bursty traffic, due to large scale network collisions [6]. Moreover, due to limited control over transmission from its decentralised nature, the performance of CSMA/CA can be highly unpredictable. There can also be bias towards certain nodes over others depending on their distance (which directly affects the received signal strength) from the PAN coordinator (the PAN coordinator is the sink node in the IEEE802.15.4 protocol). The natural approach to deal with these constraints is to exploit the inherent correlation in SHM data and performing in-network processing that results in much smaller processed data, that can fit within the bandwidth and energy constraints, as previously discussed. The alternative would be modifying the IEEE802.15.4 protocol to support heavier traffic loads and deal with bursty traffic.

Nefji and Song [13] proposed CoSenS, a collect-and-send burst scheme in which they try to improve the intrinsic performance of CSMA/CA in WSNs. CoSenS is implemented on top of the CSMA/CA protocol, where it collects data from the (children) sensors and neighbouring routers for a period of time, referred to as the *Waiting Period* (WP). At the end of WP, the router transmits all the collected data packets in a burst during a period referred to as the *Transmission Period* (TP). The performance improvements in terms of throughput, end-to-end delay and reliability have been validated using simulations, and the authors claimed that they are the first to improve other aspects of WSN performance, unlike other WSN MAC schemes which only aimed to improve energy efficiency. While throughput and reliability improvement are obvious, the delay improvement can be inferred from few collisions among network nodes, viz. routers, as compared to individual packet transmissions. CoSenS can be regarded as a subset of the WSN approaches for SHM discussed earlier, without in-network processing nor consideration for the intrinsic correlation of SHM data. The contention among the sensors transmitting to the PAN coordinator (in their case, the router) remains unaddressed.

Closer to addressing the contention issue in IEEE802.15.4-based WSNs is the scheme by Lee *et al.* [14] which aims to ensure balanced distribution of data transmission across groups/clusters of nodes in a network. Two thresholds are defined which are compared to the successful data transmission ratio (SDTR). The proposed algorithm kicks in when the SDTR falls below the lower threshold and stops when the higher threshold is crossed. The scheme operates by dividing the network into groups or clusters of nodes. The original IEEE802.15.4 superframe is modified such that the *Contention Access Period* (CAP) is divided into Group CAP (G-CAP) and Free CAP (F-CAP) where G-CAP comprises multiple *Guaranteed Time Slots* (GTS) one for each group. After the allocation of a GTS, the nodes within the group send simultaneous pulses to the coordinator if they have data to send. If the coordinator receives no pulse, that means that the group has no data to send; if the coordinator receives one pulse, it means that the group has just one data packet to send, and if the coordinator receives a garbled pulse then the group has more than one data packet to send. Future allocation of GTS depends on the number of pulses in the current round. This novel scheme of pulses is very effective for a small network, but does not scale to large network/group sizes, as nodes would spend most of their time sending pulses before actually being able to get a transmission opportunity, and thereby wasting significant time and energy. Burst traffic scenarios are also not addressed.

Research on WSNs for SHM of civil infrastructures after catastrophic rare events has explored the use of energy harvesting to drive the sensors. Given the very limited amount of energy that can be harvested from the event, Cheng *et al.* [15] proposed a modification to the IEEE802.15.4 protocol that gives higher preference to uncorrelated data rather than individual node data. The scheme ensures that at least one data packet is transmitted from each cluster at the earliest, where each cluster represents a region of interest to civil engineers. Remaining packets can be transmitted in the same manner until nodes exhaust their energy supplies. An optimal backoff time slot selection algorithm was analytically derived that aims to minimize the number of nodes selecting the same backoff slot, unlike the IEEE802.15.4 protocol whose random backoff slot selection follows a uniform distribution. This approach is critical for the stringent energy harvesting scenario considered by the authors as collisions waste energy and should be avoided at all costs. We also adopt the same non-uniform random backoff slot selection approach in our design, to be presented in the next section.

Network bias/unfairness due to capture effects has been shown to exist in CSMA/CA-based MAC protocols [16]–[18], which we have also observed (cf: Section IV-B.) WSNs are low power devices and bursty traffic coupled with capture effect can easily lead to performance degradation, if not handled properly.

This paper proposes a design to tackle the problem and compares its efficacy against existing WSN MAC protocols in dealing with capture effect and bursty traffic.

III. PROPOSED SYSTEM MODEL

We assume that all nodes are within one-hop transmission range of a Personal Area Network (PAN) coordinator that receives all the data from the sensors under its charge; e.g. PAN coordinator is installed on a lamp post that is next to a building where SHM sensors are deployed, as shown in Fig. 1.

In the design of our MAC protocol, we exploit the high degree of correlation in SHM data where more emphasis is put on transmitting uncorrelated data from different clusters evenly rather than allowing all nodes to compete for channel access individually. The clusters of sensors are defined by domain experts, e.g. structural engineers, who have the knowledge to best identify and organize nodes into clusters, such that each cluster is a set of correlated data points.

We can view each cluster as a supernode, and as soon as one node of a cluster has successfully transmitted its data, we deem

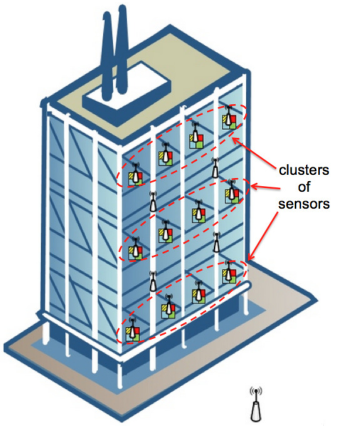


Fig. 1: Deployment Scenario (figure adapted from picture on wireless building automation in wlba.wordpress.com)

the cluster to have succeeded in the current cycle. The rest of the nodes in that cluster refrain from transmitting further until all the other clusters in the network have also succeeded in the current cycle. When the PAN coordinator successfully receives a packet from a node, it simply broadcasts an acknowledgement (ACK) packet containing the identifier of the successful node, and the other nodes in the cluster upon receiving this ACK get to know that a node in their cluster has succeeded. The nodes in this successful cluster will transition into "active listening" mode, and the cluster as a whole is said to be in active listening state when all the member nodes refrain from transmitting, but actively listen to broadcast signals from the PAN coordinator. Fig. 2a shows the state transition diagram for the PAN coordinator in the IEEE802.15.4 context.

The PAN coordinator typically remains idle until an event occurs after which it waits for data from the sensor nodes. Here, we are assuming the scenario of a rare event (like earthquake) occurrence that triggers the SHM process, although the PAN coordinator can remain in listening mode all the time (waiting for any transmission from the sensors) as it is assumed to have sustained power source. We note that even minor tremors that cause low degree of structural vibrations can trigger an event and activate the sensors. This cluster-centric approach has two advantages:

1) Higher priority is given to transmission of uncorrelated data from different clusters; this is an implicit "round-robin" that ensures fairness among clusters.
2) Nodes within a cluster have fair chance to transmit during each transmission cycle.

We build our algorithm on the standard IEEE802.15.4 non-beacon mode protocol, wherein the PAN coordinator is the sink node and solely relies on the slotted CSMA/CA mechanism to arbitrate transmission attempts by the nodes.

A critical component of the IEEE802.15.4 MAC protocol is the *Backoff Exponent* (BE). Before a node attempts to transmit a packet, it first delays for a random number of complete slot periods in the range 0 to $2^{BE}-1$ and then checks that the channel is clear/idle before it transmits. This random number is selected based on a *uniform* distribution, which means every slot in the range 0 to $2^{BE}-1$ has an equal chance of being selected by a node. In a network with many nodes wanting to transmit, this leads to a high probability of collision.

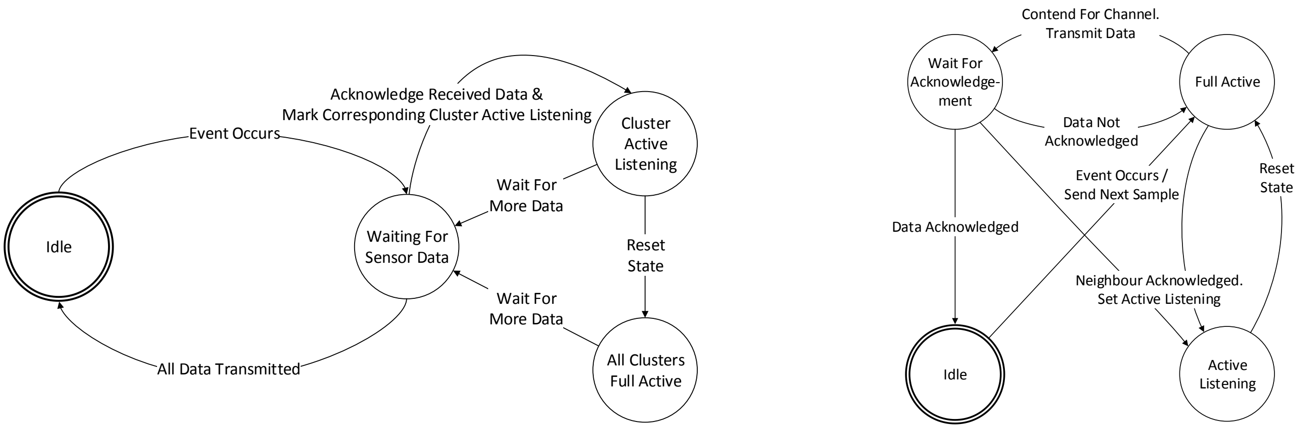
Motivated by the *optimal backoff time slot selection* algorithm proposed by Cheng *et al.* [15], we make the nodes randomly select a slot based on a geometric distribution with lower probability of selecting an early slot so that fewer nodes pick the earlier slots, reducing the chances of collisions, and have a higher chance of successfully transmitting their packets.

Every time a (node in a) cluster successfully transmits a data packet, the cluster goes to active listening state thereby bringing down the network size by one cluster, i.e. reducing the number of nodes contending for channel access subsequently, and this increases the successful transmission probability of the remaining clusters. Depending on the cluster and network size, network contention drops rapidly with each successfully transmitted packet and considerably increases the successful transmission probability of remaining clusters.

When all the clusters have transmitted one data packet each and all the clusters are in active listening state, we regard this as the end of a transmission cycle. The PAN coordinator then broadcasts a "reset" frame and the nodes that did not manage to successfully transmit their packets in the cycle that just ended try again in the next transmission cycle. This is the "Reset Cluster State" event that puts all the clusters back into "Full Active" state which is the lower-right bubble of the PAN coordinator state machine in Fig. 2a and upper-right bubble in the Sensor Node state machine in Fig. 2b. In the next transmission cycle, the network operates in the same manner as the previous transmission cycle with the only exception that the nodes which have already successfully transmitted their packets (in previous cycles) do not participate.

The decision to put a cluster to active listening state is taken autonomously at node level based on data acknowledgement broadcast by the PAN coordinator. Putting a node to active listening state simply means that the node refrains from contending for channel access to transmit, while the hardware state remains exactly as an active node. A node goes to active listening state when a neighbour node belonging to the same cluster is acknowledged for a successful packet transmission, and resets its state back to full active only when the PAN coordinator sends a reset signal as shown in Fig.2b. Once all the clusters are in active listening state, the PAN coordinator broadcasts a "reset" frame to reset all the nodes' state for next round of transmissions. To reduce the nodes' energy consumption, the PAN coordinator can also include in the ACK packet the number of remaining clusters to transmit and "active listening" nodes can estimate the quickest time required for these remaining clusters to successfully transmit, and then go to sleep for this period of time.

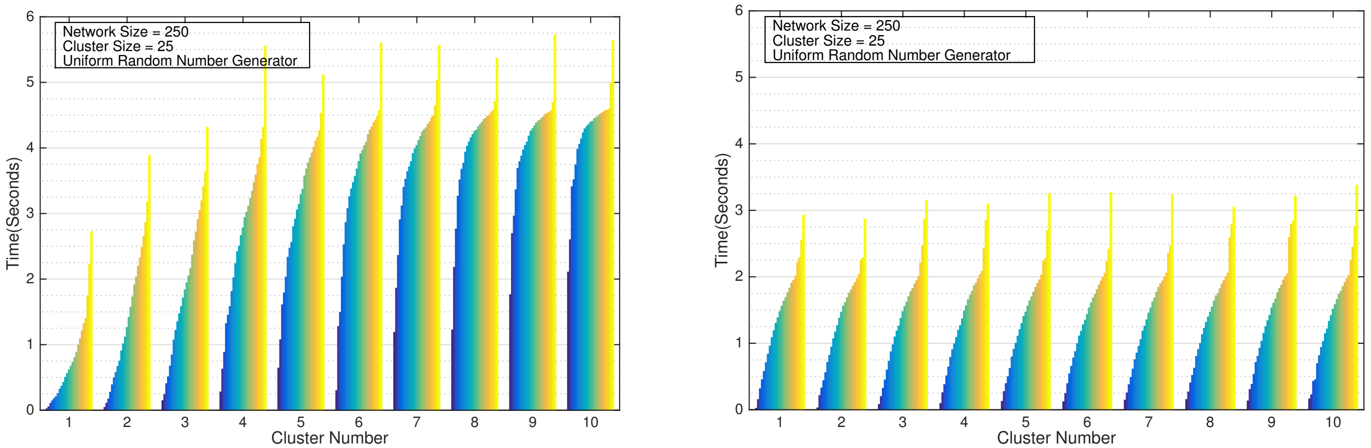
The proposed design is simple, with minor changes to the IEEE 802.15.4 MAC algorithm, yet able to achieve significant performance improvements and eliminate network bias.



(a) PAN Coordinator

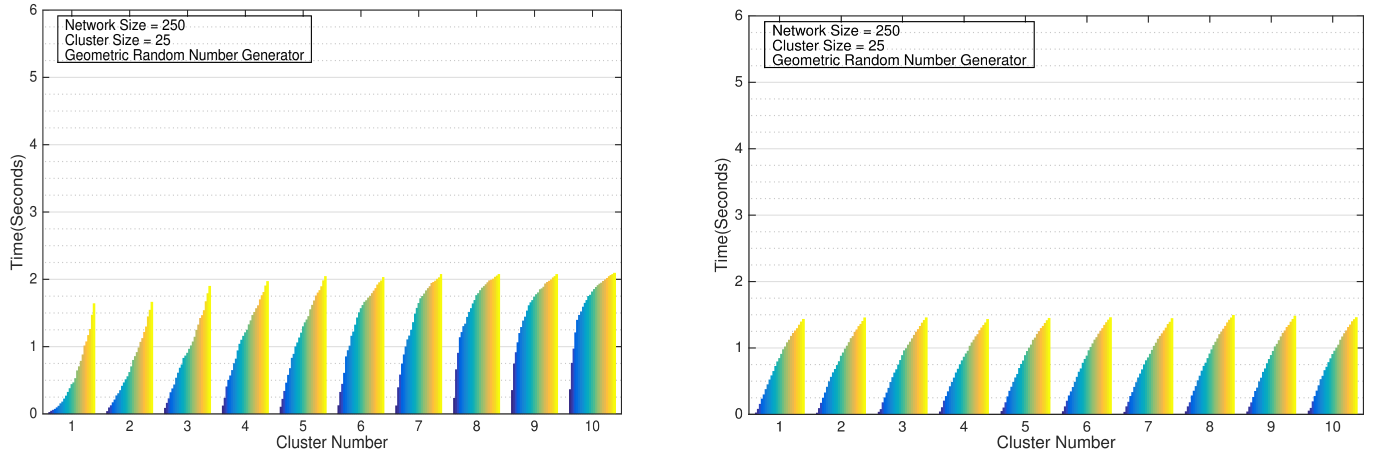
(b) Sensor Node

Fig. 2: State Transition Diagrams



(a) IEEE802.15.4 with Uniform Random Backoff Slot Selection

(b) Cluster-centric MAC with Uniform Random Backoff Slot Selection



(c) IEEE802.15.4 with Geometric Random Backoff Slot Selection

(d) Cluster-centric MAC with Geometric Random Backoff Slot Selection

Fig. 3: Packet Arrival Time (N=250, C=25)

IV. EVALUATION

This section presents the performance evaluation of the proposed design using the QualNet simulator. We compare and validate our scheme against other IEEE802.15.4 variants as well as the WSN approach proposed by Liu *et al.* [8] that employs in-network processing of SHM data.

A. Evaluation Model

The study uses the standard IEEE802.15.4 protocol, and the proposed cluster-centric MAC is built on top of that. Varying cluster sizes (5, 10, 15, 20, and 25) and network sizes (100, 150, 200, and 250) are used for the evaluation. To obtain accurate averages the result for each combination is an average of ten different runs, with each run using a different seed value.

The sensor nodes are placed as they would be in a real life SHM system. The PAN coordinator is usually outside the building and not very high above the ground, and the sensor nodes in the building with the ground floor sensor nodes closest to the PAN coordinator and the highest floor sensor nodes furthest away. Nodes in cluster #1 are closest to the PAN coordinator and the cluster numbers increase with increasing distance from the PAN coordinator. This deployment scenario is similar to that shown in Fig. 1.

For the purpose of evaluation, we assume the scenario where data are generated by the occurrence of an event (time t_0) that warrants attention, e.g. strong tremor or earthquake. After all the data generated by that event has been transmitted, the WSN goes back to sleep until another event activates it. In our targeted scenario, we assume a fixed amount of data are generated at each node as a result of an event.

The model uses a simple battery with 2400mAh initial charge, and the MICAZ Qualnet energy model. The physical and MAC layer use the default Qualnet 802.15.4 radio and reception model.

B. Time to completion in a cluster

We show one set of representative results of a series of twenty different combinations. The results for the 250-node network which is the largest network size evaluated to show the packet delivery characteristics of the IEEE802.15.4 MAC and the proposed cluster-centric MAC protocols.

Referring to Fig. 3, the vertical plots for each cluster show the time duration (since t_0) at which consecutive packets within a cluster are successfully transmitted and received by the PAN coordinator; e.g., the blue bar on the left shows the time needed by the first successfully transmitted packet of a cluster (irrespective of which sensor within the cluster it came from) and the next bar shows the second successful packet, and so forth.

In Fig. 3a and Fig. 3c, the standard IEEE802.15.4 MAC protocol produces bias towards nodes and clusters closer to the PAN coordinator node. This skewed performance for nodes/clusters closer to the PAN coordinator can be attributed to capture effect [16] which has been observed and studied in IEEE802.15.4 networks [18], [19]. This leads to clusters that are closer to the PAN coordinator node being able to transmit all their data much sooner than the clusters that are further away.

The proposed model eliminates this bias phenomenon by ensuring that each cluster gets a fair chance rather than individual nodes. This is achieved by taking a cluster (and all the nodes therein) out of the contention for the channel once it is successful in the current cycle. No bias results are observed, as reflected in Figures. 3b and 3d which show every cluster evenly sending packets to the PAN coordinator. Since there is no bias among clusters, all the clusters finish transmitting their data around the same time. This is a favorable consequence of the cluster-centric approach which reduces overall network contention and improves the entire network's performance.

Both Fig. 3a and Fig. 3c use the same IEEE802.15.4 CSMA/CA MAC algorithm but different random number generator. However, the geometric random backoff finishes faster than uniform random backoff. The same can be observed in Fig. 3b and Fig. 3d for the cluster-centric MAC. It is reasoned that by choosing a larger initial backoff there will be fewer collisions. Fewer collisions means nodes need not exponentially backoff, thus reducing the average time to complete transmitting the information generated by the event.

In the proposed model, once a node is able to successfully transmit its data packet, the corresponding cluster refrains from further transmission until the next transmission round, which helps in significant drop in contention as fewer nodes have to contend for channel access after a successful data transfer. This, coupled with geometric backoff time slot selection, further reduces contention which results in less overall contention and faster transmission times.

C. Average and Total time to transmit

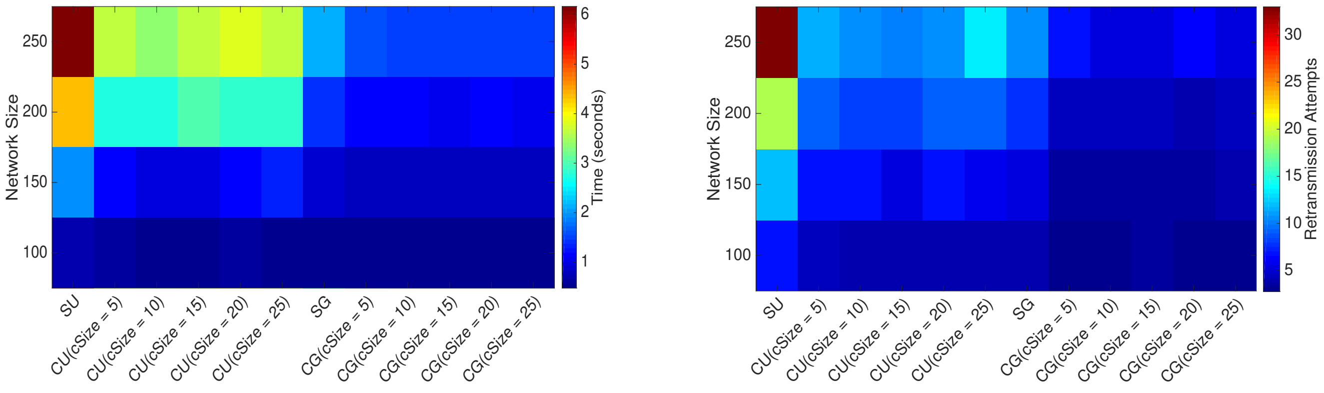
While the aim of this paper is to study the problem from cluster perspective and focus on unbiased distribution of data, this subsection aims to show some related results from a network-wide perspective.

While it is evident from Fig. 3 that the proposed scheme ensures unbiased transmission opportunities for clusters, the results also show that the event data are transmitted faster than the standard IEEE802.15.4 protocol. Fig. 4a shows the average time to transmit the event data are on average shorter with the proposed cluster-centric MAC.

The time difference for small network sizes is very small, but it becomes more significant with increasing network size due to higher contention. While the standard IEEE802.15.4 protocol shows large variation in time to completion, the proposed model gives consistent time to complete transmissions irrespective of network size.

To further understand the time to transmit all packets, where we measure the total time to transmit all packets at fixed packet error probabilities. Increased packet loss probability triggers higher retransmission rates, and a vicious cycle of successive retransmissions may develop due to the large number of nodes transmitting/retransmitting simultaneously.

Figure 5a shows that the standard IEEE 802.15.4 does suffer from high delays while cluster-centric approach experiences a



(a) Average Time To Transmit All Packets.

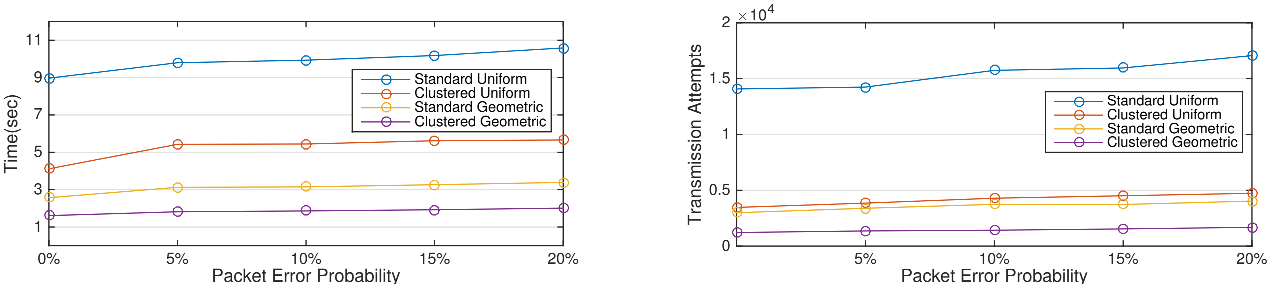
(b) Average Retransmission Attempts To Transmit All Packets.

SU : Standard IEEE802.15.4 - Uniform Random Number Generator
CU : Cluster-Centric MAC - Uniform Random Number Generator

cSize : cluster size

SG : Standard IEEE802.15.4 - Geometric Random Number Generator
CG : Cluster-Centric MAC - Geometric Random Number Generator

Fig. 4: Average Performance for Different Network & Cluster Sizes



(a) Total Time To Transmit All Packets.

(b) Total Retransmission Attempts To Transmit All Packets.

Fig. 5: Lossy Environment (N=250, C=10)

very gradual increase in time needed as the loss probability increases. Retransmissions are costly actions in terms of time and energy, hence one of the aims of WSN protocols is to minimize retransmission count. The proposed design is able to significantly reduce the network congestion by taking nodes out of the contention for the channel promptly and hence is able to transmit all its data packets much sooner than the standard IEEE802.15.4 protocol. Less contention in return means less retransmissions, and the same effect of fewer transmissions can be observed in Fig.4b and Fig.5b.

D. Energy consumption

To put the energy consumption by the proposed design into perspective, we compare our results with Liu *et al.* [8] which is an example of a WSN approach designed to reduce energy consumption by performing in-network processing of SHM data. This approach has been selected, among others, as they have provided sufficient details on their evaluation and parameter values that enabled us to do a reasonable comparison; however, we wish to state that the comparison cannot be completely fair as their simulations did not take into account the MAC protocol's functionality.

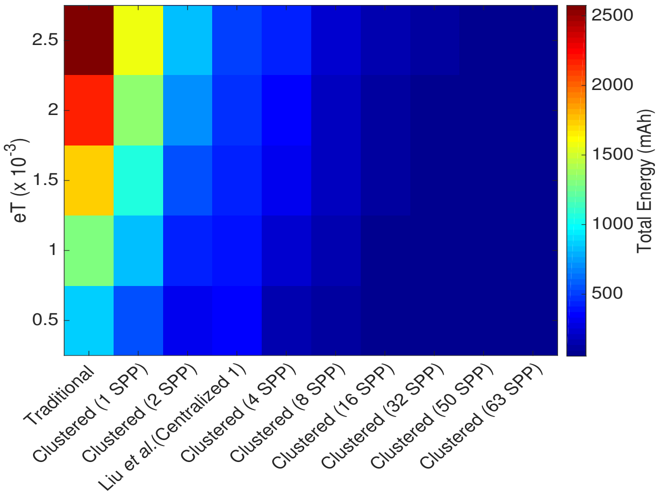


Fig. 6: Energy consumption comparison with WSN for SHM proposed by Liu *et al.* [8] where eT (y-axis) is the transmission power, measured in mAh.

A standard IEEE802.15.4 maximum payload capacity of 127 octets can support up to 63 samples of 2 octets each. We evaluated the proposed design using different sample sizes from one sample per packet (SPP) to the maximum possible 63 SPP, and assume a total of 10752 samples and energy values as specified in [8]. Our simulations produced similar results for cluster sizes 5, 6, 7 and 8, so we cite results for cluster size 5. Since smaller SPP means higher number of packets, intuitively it should mean that using 63 SPP not only results in lesser number of packets but also lesser contention, fewer retransmissions and lower energy consumption.

On the other hand, sending larger payloads require more energy than shorter payloads, but there are energy and throughput gains due to the amortization of the transmission overheads, and it has been shown that payload sizes of around 100 octets are near-optimal [20]. Hence, we also included a scenario with 50SPP to represent a 100-octet payload. Simulation results as presented in Fig. 6 also show that we are able to achieve better performance with as few as 4 SPP, without having to perform in-network processing.

V. CONCLUSION

Much of the work that has been done on smart WSNs for SHM focused on determining the optimal network structure, viz. clustering of sensors, to facilitate in-network distributed processing of SHM data for modal analysis. The aim of this approach is to reduce the bandwidth requirements imposed by voluminous raw SHM data on the network, and exploit the computational power of sensors to perform distributed computation (modal analysis) that is usually done at the data acquisition centre (or PAN coordinator). Clustering in WSNs has been extensively studied from the networking perspective with the aim of achieving optimal network performance without consideration on the content of the data being delivered. This paper looks at clustering from a new perspective and utilizes clustering in novel way to address an unstudied problem of biasness towards nodes that are closer to the PAN coordinator.

The proposed cluster-centric MAC protocol treats each cluster as a supernode when arbitrating access to the wireless channel, and has been shown to significantly reduce contention leading to improved network performance overall. The design performs consistently better compared to existing WSN MAC protocols, especially, in bursty traffic conditions. The design gives unbiased packet delivery at the sink, in addition to faster transmission times, reduced contention and energy usage.

As SHM deployment scenarios are also susceptible to high levels of signal interference due to structural properties (like metallic beams), and the presence of other wireless networks, WSNs used in SHM must be robust against transmission errors. In this aspect, we have also shown that our design is less susceptible to increasing packet errors under error prone conditions. Moving forward, extensions to the current design include autonomous dynamic clustering, and the ability to operate with energy harvesting as a power source.

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