Distributed Medium Access Control with Flow-based Priority for Cooperative Multi-hop Wireless Sensor Networks

T. Owens Walker III, Murali Tummala, and John McEachen
Department of Electrical and Computer Engineering
Naval Postgraduate School, Monterey, California, USA
{towalker, mtummala, mceachen}@nps.edu

Abstract

Medium access control for a distributed cooperative wireless sensor network is examined. Using a quality-of-service approach, the sensor node traffic (control and data packets) within these cooperative networks is characterized. A novel medium access control mechanism, Cooperative Wireless Sensor Medium Access Control (CWS-MAC), is proposed to meet the requirements of the control and data traffic classes. CWS-MAC couples a high throughput TDMA scheme with a unique cross-layer, flow-based priority mechanism that is enforced across nodes. Design parameters for CWS-MAC are investigated and an implementation strategy is presented. Performance analysis of CWS-MAC is provided for the control packet mean delay as well as control and data packet throughput. Simulation results are provided to demonstrate that CWS-MAC outperforms both traditional TDMA and contention-based CSMA.

1. Introduction

Wireless sensor networks have traditionally been comprised of large numbers of small, densely-populated sensor nodes that are constrained in power, processing capability, and memory [1,2]. Current research, though, is envisioning applications that stretch the capabilities of both the sensor nodes themselves and the underlying network that supports them. Recent work in wireless sensor and actor networks [3], wireless multimedia sensor networks [4], and distributed beamforming in wireless sensor networks [5] considers bandwidth-intensive wireless networks that are comprised of large numbers of sophisticated nodes capable of action in response to control input.

These applications share a need to provide internode control (packet) communication despite the presence of a large volume of sensor data traffic. In a wireless multimedia application, for example, video camera-equipped nodes transmit high-bandwidth streaming video while camera control inputs (e.g., camera movement and lens focus) must be injected into the network traffic to optimize sensor node and resource utilization [4]. Similarly, in the case of distributed beamforming, the transmission of complex weights to the participating nodes to form the beam competes directly with the high-bandwidth sensor data that will be transmitted through the beam [5].

These challenges can be viewed as a Quality-of-Service (QoS) problem within the constraints of the wireless sensor network. In each case, the sensor data packets and sensor control packets form two distinct traffic classes that must be handled effectively and efficiently by the network. Significant work has been done in medium access control for wireless sensor networks [6], but as sensor nodes become more sophisticated, the need to accommodate the requirements of both sensor data traffic and sensor control traffic becomes critical.

This paper applies a QoS approach to medium access control in cooperative wireless sensor networks by characterizing the primary traffic flows, outlining the design objectives, and proposing a global, cross-layer, flow-based priority mechanism. The primary contribution of this work is the proposal of a novel medium access mechanism to achieve these design goals. The Cooperative Wireless Sensor Medium Access Control (CWS-MAC) protocol is a distributed, cross-layer medium access solution for wireless sensor networks. It is the first proposed MAC solution that provides an internode, flow-based priority mechanism to support the demands of dynamic, controllable sensor nodes in the context of high bandwidth sensor data traffic. Specifically, it utilizes a QoS approach to provide high throughput for sensor data and minimum end-to-end delay for sensor control packets.

The paper is organized as follows. Section 2 characterizes the traffic flow classes of a cooperative wireless sensor network and identifies a set of medium access design goals. CWS-MAC and its associated parameters are presented in Section 3 and a set of implementation guidelines is offered. A performance analysis of the sensor control packet delay and the sensor data and control traffic throughput is performed in Section 4 and simulation results are presented in Section 5.

2. Medium Access in Cooperative Wireless Sensor Networks

In cooperative wireless sensor networks, application traffic can be divided into two distinct QoS classes. As can be seen in applications such as wireless multimedia sensor networks [4], the data traffic is typically bandwidth-intensive but is tolerant to individual packet loss because the sensor data are correlated in both time and space. The associated control packet traffic required to effectively utilize the capabilities of the dynamic sensor nodes comprises the second class of traffic. This traffic typically requires an end-to-end delay bound and is not tolerant to losses but utilizes significantly less bandwidth. In general, for this traffic class, the packets are smaller and do not arrive as frequently but must be transmitted quickly and reliably.

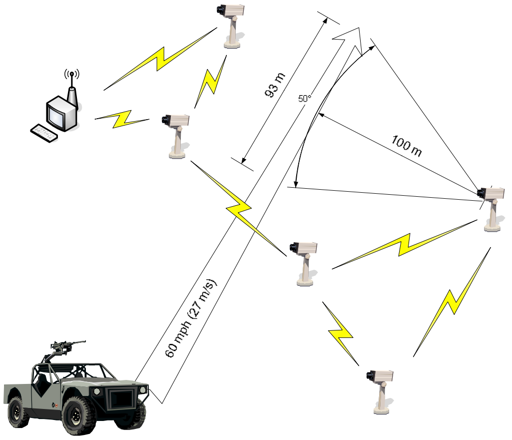

Figure 1. Example of cooperative wireless sensor network battlefield application.

An example of a battlefield application of a cooperative wireless sensor network is shown in Figure 1. Here, the sensor network is comprised of a field of rotating video cameras. If the cameras have a 50 degree field of view, they will be able cover up to 93 m of target track at a distance of 100 m. As a high speed 60 mph (27 m/s) target passes through the field, camera rotation updates will occur on the order of once every second to keep the target centered and will be triggered by control packets sent from the sink (the command and control node). These control packets need to be successfully transmitted despite the large data flow generated by the sensor field cameras. If each camera is capable of producing 320x240, 8-bit monochrome images at a frame rate of up to 20 fps, then the per node raw image data rate would be in excess of 12 Mbps.

The proposed medium access control solution should therefore meet the primary service requirements for both classes of traffic. Specifically, it should provide a high throughput solution to support the sensor data packets and a reliable solution with minimum end-to-end delay to support the control packet flow. Additionally, to provide robustness, it is desirable that the design be distributed so that each node is able to make a local transmission decision for each class of traffic. Finally, the protocol should support multi-hop networks in which all nodes are capable of handling all classes of traffic.

3. CWS-MAC

The Cooperative Wireless Sensor Medium Access Control (CWS-MAC) protocol is designed to meet the high throughput requirements for the high bandwidth sensor data flow while providing priority access to the medium for the time-critical control packet flow. Priority is based on application flow rather than node identity and, therefore, requires that the medium access layer be application-aware. This flow priority is enforced globally across nodes rather than locally within each node (i.e., a node with a control packet has priority over another node with a data packet). Additionally, an acknowledgment-based reliability mechanism is included to support the loss-intolerant control traffic flow.

3.1 CWS-MAC Operation

To support the high bandwidth requirements of the sensor data flow, a Time Division Multiple Access (TDMA)-based mechanism is selected. Nodes are assigned slots for data traffic transmission within the TDMA frame.

Expanding on the work of [7], multiple nodes with pending control packet transmissions can “seize” the next data slot for use as a control slot. This is accomplished by providing a beacon mechanism for a node (or multiple nodes) to declare a slot as a control slot. When a node has a control packet, it transmits a control beacon at the beginning of the next available slot for a time period, t_b. Prior to transmitting a data packet in its assigned slot, a node senses the medium after a specified delay called the data interframe spacing delay, t_{DIFS}. Thus, upon hearing the control beacon, the node with the data packet will defer to the node(s) with the control packet(s) and the slot will be allocated as a control slot.

To avoid simultaneous multiple control packet transmissions that may lead to collisions, the control slot is divided into a series of control minislots. Each control minislot is designed to support the transmission of a single control packet followed by one or more acknowledgements. Upon "seizing" a control slot, a node will select a specific minislot for transmission based on a random, uniform distribution. In the case of multiple acknowledgements, the order in which the nodes acknowledge the control packet can be specified within the control packet itself. To improve data throughput, the slot owner is allowed to transmit queued data packets in the remaining slot time unused by the control minislots. The format of a CWS-MAC frame is shown in Figure 2.

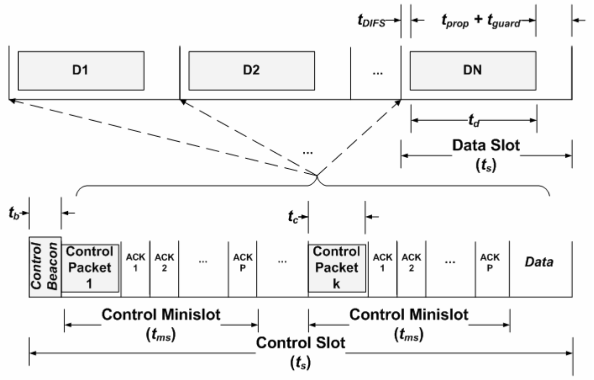

Figure 2. CWS-MAC frame with data and control slots.

It should be emphasized that although it is overlaid on top of a contention-free data transmission scheme, the control packet transmission scheme is still a contention-based approach in which losses due to collisions can occur. The acknowledgements are provided to prevent loss of the control packets which can be caused by either collisions or transmission errors. The data packet transmission scheme, on the other hand, is a contention-free, scheduled approach designed to maximize the throughput of the sensor data traffic. In light of this, CWS-MAC can be viewed as a hybrid mechanism that combines the high throughput associated with scheduled approaches with the reduced mean delay found in contention-based approaches, such as Aloha [8] and carrier sense multiple access (CSMA) [9].

Primary design parameters in this scheme include t_b, t_{DIFS}, and k, the number of control minislots within a control slot. We investigate these parameters in detail and provide a strategy for parameter selection in the following discussion.

3.2 The timing parameters t_b and t_{DIFS}

From a physical layer standpoint, the control beacon must be long enough to be detected by the sensor nodes within communication range of the transmitting node. This paper will not go into the specifics of the physical layer signal-to-noise ratio (SNR) and the resulting probability of detection calculations, but a related analysis can be found in [10].

The control beacon length, t_b, is also constrained by its relationship to the data interframe spacing period t_{DIFS}. To ensure that a consistent value can be chosen for t_{DIFS} across the network, it can be shown that the beacon reception period for the most distant node must overlap with that of the node closest to the transmitting node. This requirement results in the following bound on t_b:

$$t_b > \max\left(T_{prop}\right) - \min\left(T_{prop}\right) \tag{1}$$

where T_{prop} is the propagation time from the transmitting sensor node to the receiving sensor node. The data interframe spacing value should then be selected to lie within this overlapping time period. Conservatively assuming the minimum propagation time within the network to be zero, this condition can be shown to be equivalent to

$$t_b > t_{DIFS} > t_{prop} \tag{2}$$

where $t_{prop} = \max(T_{prop})$ is defined as the maximum propagation time experienced by the network.

3.3 Slot size and slot assignment

In CWS-MAC, the slot size is fixed and is governed by both the data packet flow and the control packet flow since a slot can act as either a data slot or a control slot. For a data slot, the slot size, t_s, is bounded by

$$t_s \geq t_{DIFS} + t_d + t_{prop} + t_{guard} \tag{3}$$

where t_d is the transmission time of a single data packet and t_{guard} is an interval provided to accommodate timing synchronization errors between sensor nodes. For a control slot, the slot size is bounded by

$$t_s \geq t_b + k\left(t_c + t_{ack} + 2t_{prop} + t_{guard}\right) \tag{4}$$

where k is the number of control minislots in a control slot, t_c is the transmission time of a single control packet, and t_{ack} is the transmission time of a single acknowledgement packet. The inclusion of t_{prop} in (3) and (4) prevents a distant node from transmitting in its assigned time slot before the previous packet has cleared the network. This buffer is required due to the broadcast nature of the wireless medium.

By combining (3) and (4), we can arrive at a relationship between t_d and k. Selecting the equality in (3) and substituting into (4), we find that

$$\begin{aligned} t_d \geq t_b - t_{DIFS} + k\left(t_c + t_{ack}\right) \\ + \left(2k-1\right)t_{prop} + \left(k-1\right)t_{guard} \end{aligned} . \tag{5}$$

This relationship allows the development of a design strategy which we discuss in the next subsection to assist in the selection of the parameters for a CWS-MAC implementation.

CWS-MAC operation is not contingent on the selection of a specific slot assignment scheme, although the chosen scheme can significantly impact network performance. To accommodate changes in network topology due to node mobility, node failure, and changes in the link quality, TDMA-based medium access schemes designed for wireless sensor networks typically incorporate a dynamic assignment scheme based on a reservation phase followed by one or more data transmission phases as introduced in [11]. In these approaches, the overhead of the assignment process varies with the frequency of the reservation phase.

3.4 CWS-MAC Parameter Selection

In this subsection, we present a potential strategy for selecting values for the parameters identified previously. These parameters include the slot size t_s, the control minislot size t_{ms}, the number of control minislots k, the length of t_b and t_{DIFS}. In a given implementation, we begin with the physical characteristics of the network which include the network data rate, the number of nodes in the network, and the maximum internode spacing from which we can determine the maximum propagation time t_{prop}. As with any TDMA-based scheme, slot synchronization is required and the precision of the time synchronization algorithm utilized determines the guard band t_{guard}. The size of the control packets is determined by the complexity of the sensor node control instructions and the size of the acknowledgements can be fixed in the protocol design to be as small as possible. Respectively, these provide t_c and t_{ack}.

The control beacon length, t_b, and the data interframe spacing, t_{DIFS}, should be selected to meet the constraints of (1) and (2). As we shall see in the next section, the number of control minislots, k, determines the probability of collision and subsequent retransmission. Accordingly, k should be selected to be large enough to meet some desired probability of successful transmission. Once we have fixed k, we can now calculate t_d as in (5) to maximize data packet throughput.

4. Performance Analysis

In this section, we calculate the mean delay experienced by a sensor control packet and the throughput of the data packet flow. This analysis assumes that both the control and data packet arrival processes are Poisson. Additionally, without a loss of generality, it is assumed that each node is assigned a single slot in a frame.

4.1 Control Packet Mean Delay

We define the mean delay, $\overline{D_c}$, experienced by a control packet to be the difference between the time a control packet arrives at a node for transmission and the time it is successfully transmitted. This mean delay can be found by analyzing the effect of control packet collisions and subsequent retransmissions on delay performance. The mean delay of a packet that experiences no collisions and is transmitted in the first control minislot can be shown to be

$$\overline{D_{nc1}} = \frac{t_s}{2} + t_b + t_c + t_{prop} . \tag{6}$$

Control packets that encounter no collisions but are transmitted in later minislots experience the additional delay of each subsequent minislot, t_{ms}. Assuming that the minislot selection is a random process with a uniform distribution, the mean delay for a packet encountering no collisions is

$$\overline{D_{nc}} = \overline{D_{nc1}} + \frac{k}{2}t_{ms} . \tag{7}$$

To capture the effect of collisions, we observe that each time a control packet experiences a collision, the delay for that packet is increased by a single slot time, t_s, since the node must now wait until the next slot to attempt to retransmit the packet. From this, we can show that the delay of a control packet that experiences j consecutives collisions is given by

$$\mathrm{D}_{\mathrm{cm}} = \mathrm{D}_{\mathrm{nc}} + jt_s . \tag{8}$$

The overall mean delay is then

$$\overline{D_c} = \sum_{j=0}^{\infty}\left(\overline{D_{nc}} + jt_s\right)p_j \tag{9}$$

where p_j is the probability that a control packet will encounter j consecutive collisions. Substituting (7) into (9) and simplifying, we arrive at the expression

$$\overline{D_c} = \overline{D_{nc1}} + \frac{k}{2} t_{ms} + t_s \sum_{j=0}^{\infty} j p_j \, . \tag{10}$$

To calculate the expression for p_j, we use the fact that the control minislot selection is a random process with a uniform distribution. The probability of j consecutive control packet collisions is then found to be

$$\begin{aligned} p_j &= \left(1 - p_0\right)^j \qquad \text{for } j = 1, 2, \ldots \infty \\ p_0 &= \left(\frac{k-1}{k}\right)^{\overline{M}-1} \end{aligned} \tag{11}$$

where $\overline{M}$ is the mean number of nodes that have a control packet queued for transmission at the beginning of a given slot. A node will have a control packet queued for transmission if a control packet arrived in the previous slot. Therefore,

$$\overline{M} = \left(1 - e^{-\lambda_c t_s}\right) n \tag{12}$$

where λ_c is the aggregate control packet arrival rate and n is the number of nodes in the network. The probability of control packet collisions is plotted as a function of control traffic load for multiple values of k in Figure 3. As expected, the probability of collision p_j increases with control traffic load and decreases as k increases.

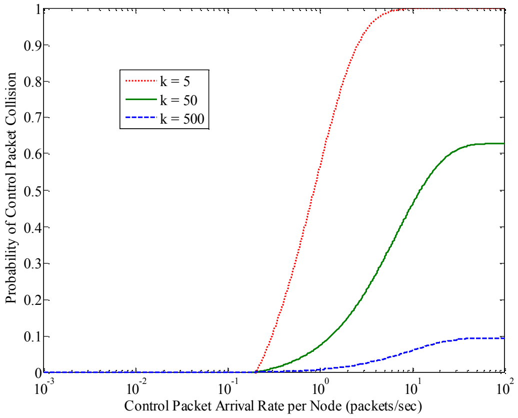

Figure 3. Probability of collision vs control packet load for multiple values of *k*.

Assuming k is chosen such that the probability of control packet collisions is negligible, the expected control packet delay of CWS-MAC is compared to traditional TDMA and CSMA in Figure 4. CWS-MAC can be seen to significantly outperform TDMA, but suffers from the overhead associated with the scheduled slot scheme when compared to CSMA. For TDMA and CSMA, it is assumed that the control flow is handled using a priority queue scheme that provides head of the queue privilege to the arriving control packets. The CSMA delay can be seen as best case since it does not include retransmissions due to collisions and does not reflect the decrease in CSMA control packet throughput at higher loads which is presented in the following section. Details of the TDMA delay performance analysis can be found in [12].

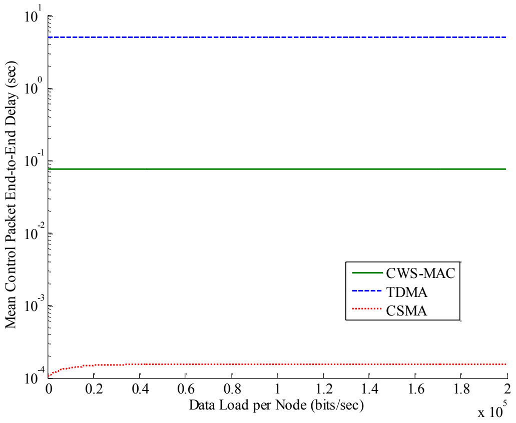

Figure 4. Expected control packet delay of CWS-MAC, TDMA and CSMA for 50 nodes with a per node control packet arrival rate of 1 packet/sec, a maximum internode distance of 750 m, a slot size of 0.1 sec, a control minislot size of 1 msec, and 50 minislots per slot.

4.2 Sensor Data Throughput

For a data slot, it can be easily shown that the normalized sensor data throughput for CWS-MAC is given by

$$S_{dd} = \frac{t_d}{t_s} \tag{13}$$

where

$$t_d = t_s - t_{DIFS} - t_{prop} - t_{guard} \tag{14}$$

from the equality in (3). For a control slot, however, the data throughput is reduced to

$$S_{dc} = S_{dd} - \left(\frac{t_b + k t_{ms}}{t_s}\right). \tag{15}$$

Therefore, the throughput for the sensor data flow will decline as nodes reallocate data slots to control slots to allow the transmission of queued control packets. To account for this reduction in throughput, we need to calculate how many slots, on average, will be reallocated as control slots. Assuming that *k* is chosen such that the probability of control packet collisions is negligible, the probability that a slot will not be reallocated as a control slot is equivalent to the probability that there will not be a new control packet arrival at any of the network nodes during the prior slot. Thus, the normalized data throughput is

$$\begin{aligned} S_d &= \Pr\left[\text{no control arrivals}\right] S_{dd} \\ &\quad + \Pr\left[\text{at least one control arrival}\right] S_{dc} \end{aligned} . \qquad (16)$$

Given Poisson arrivals, the normalized data throughput for CWS-MAC can be expressed as

$$\begin{aligned} S_d &= \left(e^{-\lambda_c t_s}\right)\left(\frac{t_d}{t_s}\right) \\ &\quad + \left(1 - e^{-\lambda_c t_s}\right)\left(\frac{t_d - t_b - k t_{ms}}{t_s}\right) \end{aligned} \qquad (17)$$

where λ_c is the aggregate control flow arrival rate (packets/sec).

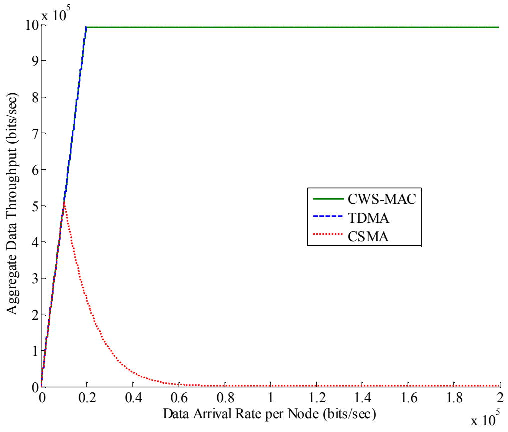

Figure 5. Maximum sensor data throughput (control packet arrival rate of 0 packets/sec) of CWS-MAC, TDMA and CSMA for 50 nodes with a channel data rate of 1 Mbps, a maximum internode distance of 750 m, a slot size of 0.1 sec, a control minislot size of 1 msec, and 50 minislots per slot.

In Figures 5, 6, and 7, the throughput performance of CWS-MAC is compared to classical TDMA and CSMA. The maximum achievable data throughput of CWS-MAC is close to TDMA as seen in Figure 5 and outperforms CSMA as the latter becomes saturated at higher network loads. The difference in maximum achievable data throughput between TDMA and CWS-MAC can be attributed to the overhead associated with t_{DIFS}. As expected, the introduction of control packet arrivals in Figure 6 results in a reduction in the aggregate data throughput for CWS-MAC, although it still outperforms the purely contention-based protocol at high data loads. Finally, in Figure 7, we see the collapse of the CSMA control throughput as the network becomes saturated at the higher loads while the scheduled approaches of TDMA and CWS-MAC allow the control flow throughput to be insensitive to the data traffic load. Details of the CSMA throughput performance analysis can be found in [9].

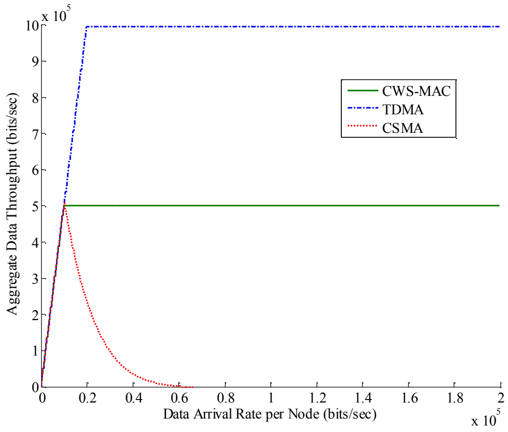

Figure 6. Sensor data throughput of CWS-MAC, TDMA and CSMA for 50 nodes with a channel data rate of 1 Mbps, a per node control packet arrival rate of 1 packet/sec, a maximum internode distance of 750 m, a slot size of 0.1 sec, a control minislot size of 1 msec, and 50 minislots per slot.

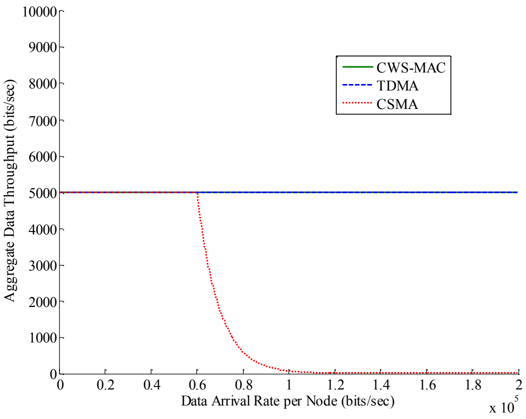

Figure 7. Control flow throughput of CWS-MAC, TDMA and CSMA for 50 nodes with a channel data rate of 1 Mbps, a per node control packet arrival rate of 1 packet/sec, a maximum internode distance of 750 m, a slot size of 0.1 sec, a control minislot size of 1 msec, and 50 minislots per slot.

5. Simulation Results

Simulation results are provided in Figures 8, 9, 10 and 11 to compare the control packet delay as well as data and control packet throughput of CWS-MAC to that of traditional TDMA and CSMA. In Figure 8, we see that CWS-MAC control packet delay is more than an order of magnitude better than TDMA. The specific improvement depends on the size and number of slots in a frame. Although the CSMA control packet delay appears to be better than both CWS-MAC and TDMA, it should be emphasized that the control packet throughput for CSMA dramatically drops off with increasing data loads as can be seen in Figure 9. The CWS-MAC and TDMA control throughput, on the other hand, is seen to be insensitive to the data load. In Figure 10, the maximum achievable data throughput of CWS-MAC is comparable to TDMA while the introduction of the control traffic flow results in the anticipated reduction in data throughput for CWS-MAC in Figure 11. For both cases, the data throughput for CSMA can be clearly seen to drop off in the face of high data loads. In summary and following the analytic findings of Section 4, the simulation results reflect that, unlike CSMA, CWS-MAC throughput is not sensitive to network saturation and that CWS-MAC provides improved delay performance over TDMA.

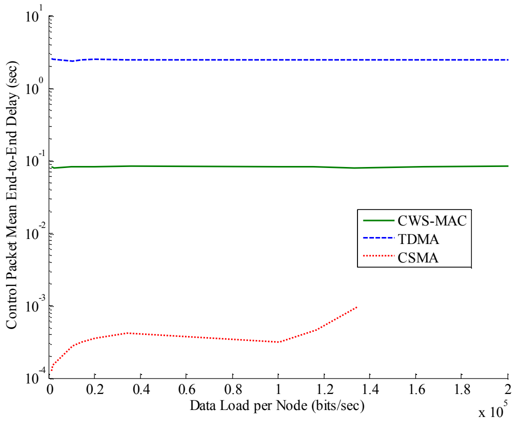

Figure 8. Simulation results for mean end-to-end control packet delay of CWS-MAC, TDMA and CSMA for 50 nodes with a channel data rate of 1 Mbps, a per node control packet arrival rate of 1 packet/sec, a maximum internode distance of 750 m, a slot size of 0.1 sec, a control minislot size of 1 msec, and 50 minislots per slot.

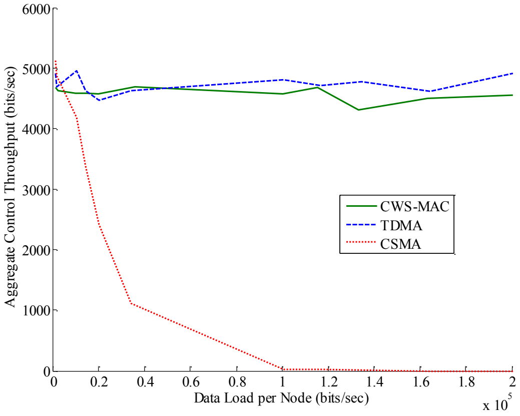

Figure 9. Simulation results for aggregate control data throughput of CWS-MAC, TDMA and CSMA for 50 nodes with a channel data rate of 1 Mbps, a per node control packet arrival rate of 1 packet/sec, a maximum internode distance of 750 m, a slot size of 0.1 sec, a control minislot size of 1 msec, and 50 minislots per slot.

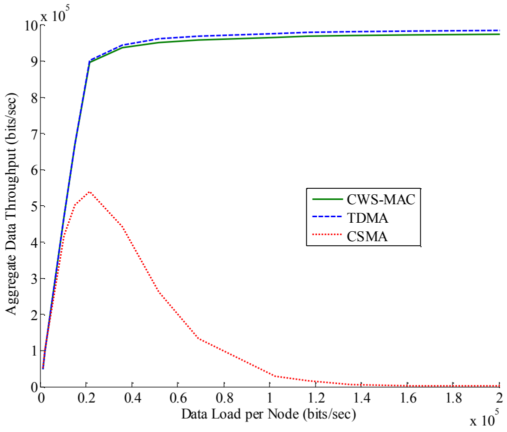

Figure 10. Simulation results for maximum data throughput (per node control packet arrival rate of 1 packet/sec) of CWS-MAC, TDMA and CSMA for 50 nodes with a channel data rate of 1 Mbps, a maximum internode distance of 750 m, a slot size of 0.1 sec, a control minislot size of 1 msec, and 50 minislots per slot.

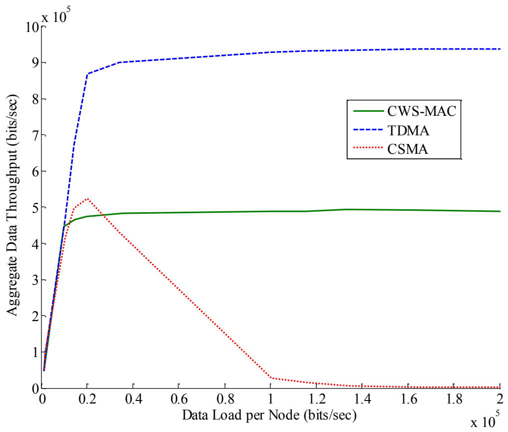

Figure 11. Simulation results for aggregate sensor data throughput of CWS-MAC, TDMA and CSMA for 50 nodes with a channel data rate of 1 Mbps, a per node control packet arrival rate of 1 packet/sec, a maximum internode distance of 750 m, a slot size of 0.1 sec, a control minislot size of 1 msec, and 50 minislots per slot.

6. Conclusions

Using a QoS-oriented approach, this paper characterizes the traffic flows associated with a cooperative wireless sensor network and proposes a novel medium access mechanism, CWS-MAC, to meet the requirements of these traffic classes. CWS-MAC combines a dynamic TDMA scheme with an application flow-based, internode priority mechanism. Design parameters are investigated and an implementation strategy for parameter selection is provided. Performance analysis is presented for both the mean control packet delay and the data and control packet throughput. Finally, simulation results are presented to show that, unlike the contention-based CSMA approach, CWS-MAC throughput is not sensitive to network saturation and that CWS-MAC provides improved control packet delay performance over traditional TDMA.

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