On the Interdependence of Congestion and Contention in Wireless Sensor Networks

Mehmet C. Vuran Vehbi C. Gungor
School of Electrical & Computer Engineering
Georgia Institute of Technology,
Atlanta, GA 30332
Email:{mcvuran, gungor}@ece.gatech.edu

Özgür B. Akan
Department of Electrical Engineering
Middle East Technical University
Ankara, Turkey, 06531
Email: akan@eee.metu.edu.tr

Abstract

Wireless Sensor Networks (WSNs) are characterized by the collaborative information transmission from multiple sensor nodes observing a physical phenomenon. Due to the limited capacity of shared wireless medium and memory restrictions of the sensor nodes, channel contention and network congestion can be experienced during the operation of the network. In fact, the level of local contention and the network congestion are closely coupled due to the multi-hop nature of sensor networks. Therefore, the unique characteristics of WSN call for a comprehensive analysis of the network congestion and contention under different network conditions. In this paper, we comprehensively investigate the interactions between contention resolution and congestion control mechanisms in WSN. An extensive set of simulations are performed in order to quantify the impacts of several network parameters on the overall network performance. The results of our analysis reveal that local interactions between sensor nodes directly affects the overall performance. The interdependency between network parameters call for adaptive cross-layer mechanisms for efficient data delivery in WSN.

1. Introduction

Wireless Sensor Networks (WSNs) are characterized by the collaborative information transmission from multiple sensor nodes observing a physical phenomenon. In WSNs, the distinct changes in the physical phenomenon are referred to as *events*, which are reported to a single controller point, i.e., sink, in a multi-hop manner. Due to the memory restrictions of the sensor nodes and limited capacity of shared wireless medium, network congestion may be experienced during the network operation. Congestion leads to both waste of communication and energy resources of the sensor nodes and also hampers the event detection reliability because of packet losses [2]. Hence, it is mandatory to address the congestion in the sensor field to prolong the network lifetime, and to provide the required quality of service (QoS) that WSN applications demand.

Unlike the conventional congestion phenomenon in wired networks, in WSNs, there exist many reasons that can lead to overall network congestion. Communication in a shared wireless medium in WSNs constitutes one of the main sources of congestion, which has not been considered in conventional congestion control protocols. Moreover, the multi-hop nature of the WSN creates additional reasons for network congestion. The main sources for network congestion in WSNs can be classified as follows:

Channel Contention and Interference: In WSNs, the local channel contention in the shared communication medium causes overall network congestion. Channel contention may occur between different flows passing through the same vicinity and between different packets of the same flow. Consequently, due to channel contention, the outgoing channel capacity of a sensor node becomes time-variant. This time-variant nature makes the node's congestion level fluctuating and unpredictable even in case of constant incoming traffic rate. Moreover, high density of sensor nodes in the network topology exacerbates the impact of the channel contention.

Number of Event Sources: The number of nodes transmitting event features in WSN directly affects both the efficiency of the network protocols and the accuracy of the event information. Although higher number of event sources can improve the accuracy of the event information, the multi-hop nature and the local interactions between sensor nodes can degrade the network performance.

Packet Collisions: Increasing network contention causes an increase in packet collisions in the wireless medium. Based on the underlying medium access control (MAC) mechanism, after several unsuccessful retransmissions, these packets are dropped at the sender node. As a result, the decrease in buffer occupancy due to these drops may indicate lower congestion when only buffer level is used for congestion detection. Therefore, for accurate congestion detection in WSNs, a hybrid approach is required.

Reporting Rate: Mainly, WSN applications can be classified into two classes, i.e., event-driven and periodic [4]. In event-driven applications, the reporting rate of sensor nodes may change during the lifetime of the network. Whereas, applications with periodic traffic, necessitate controlling the reporting rate for the proper operation of the network. In both cases, as a result of increased reporting rate, overall network congestion occurs even if local contention is minimized. Due to its collective and multi-hop nature, however, a collaborative approach is required in controlling flow rates in WSN.

Many-to-One Nature: Due to the collaborative nature of the WSNs, the packet transmission about an event from multiple sensors to a single sink may create a bottleneck, especially around the sink. Hence, this many-to-one nature also creates congestion in the network.

The reasons for congestion in WSNs, as briefly explained above, are directly related to the local interactions of sensor nodes in the network. In other words, local interactions among sensor nodes influence the overall network performance. For example, controlling contention between sensor nodes has positive effects in reducing the end-to-end network congestion. Furthermore, it has been demonstrated that for efficient congestion detection in WSNs, the sensor nodes should be aware of the network channel condition around them [5],[8].

Recently, a number of congestion control algorithms have been proposed for WSNs [2],[5],[8]. Majority of these algorithms state that cross-layer interactions between transport layer and MAC layer are imperative for efficient congestion detection and hence congestion control. In [8], channel load information from the MAC layer is incorporated into congestion detection and control mechanisms. In a converse approach, the authors in [9] propose transmission control scheme for use at the MAC layer in WSN. In [2], congestion detection is performed through buffer occupancy measurements. In [1], the backoff window of each node is linked to its local congestion state. Furthermore, [5] compares the buffer occupancy-based and channel load-based congestion detection mechanisms. Moreover, it has been experimentally shown that a hybrid approach would lead to most efficient results. It has been advocated in [5] that MAC layer support is beneficial in congestion detection and control algorithms.

Overall, it is clear that cross-layer approaches in congestion detection and control is necessary in WSN due to the close coupling between local contention and network-wide congestion. Despite the considerable amount of research on several aspects of congestion control in WSN, the interdependence of congestion and contention are yet to be efficiently studied and addressed. Therefore, the unique characteristics of WSN call for a comprehensive analysis of the network congestion and contention under different network conditions. In this work, we overview the interactions between contention resolution and congestion control mechanisms and try to find answers to the following questions:

- *What are the consequences of independent operations of local contention resolution and end-to-end congestion control mechanisms?*
- *What is the effect of local retransmissions on end-to-end congestion and reliability in WSNs?*
- *What are the effects of network parameters such as buffer sizes of the sensors, number of sources and contention window size on network congestion and contention?*
- *Can cross layer interaction be performed by preserving the modularity of layered design or are cross-layer designs required?*

The remainder of the paper is organized as follows. In Section 2, an overview of the performance metrics and the evaluation environment are described. The main results of our analysis is presented in Section 3. More specifically, the effects of number of sources, buffer size, MAC layer retransmissions, and contention window on various network performance metrics are investigated in Sections 3.1, 3.2, 3.3, 3.4, respectively. The reasons for packet drops and the effects on energy efficiency are explored in Sections 3.5 and 3.6. Finally, the paper is concluded in Section 4 along with possible approaches for efficient event transport in WSN.

2 Evaluation Environment and Performance Metrics

The goal of our work is to investigate the interactions between local contention and network-wide congestion. As discussed in Section 1, a thorough analysis of contention resolution and congestion control mechanisms are required. In order to provide such an analysis, we set up an evaluation environment using *ns-2* [6]. The simulations are performed using this environment in a 100x100m^2 sensor field. 100 sensors are randomly deployed in this field and one sensor node is selected as the *sink* node. All other sensors transmit their information to the sink when an event occurs in their sensing range. The parameters used in the simulations are shown in Table 2. Unless otherwise specified in the paper, these parameters are used in the simulations. In each simulation, events are randomly generated in random locations and nodes inside a certain event radius become source nodes and start to send information to the sink. Furthermore, the network topology is fixed for each set of experiments, and the average results for 5 different randomly generated topologies are used.

Parameter	Value
Area of sensor field	100x100 m^2
Number of sensor nodes	100
Radio range of a sensor node	40 m
Packet length	30 bytes
IFQ length	50 packets
Retransmission Limit	7
Transmit Power	0.660 W
Receive Power	0.395 W
Sleep Power	0.035 W
Event radius	30 m
Simulation Time	40 s

Table 1. NS-2 simulation parameters

Using this evaluation environment, the following performance metrics are investigated:

Event Reliability (R_{ev}): As discussed in [2], WSN requires a collective event reliability notion rather than traditional end-to-end reliability. Therefore, the total number of packets received about an event from all the nodes inside the event radius is of importance in WSN. We define the reliability as the percentage of total sent packets that are received at the sink.

Collisions: The performance of the WSN depends on the efficient usage of the wireless medium. Hence, the underlying MAC layer performance directly affects the overall performance including the reliability and energy efficiency. The number of collisions represents the contention level around the sensor nodes.

MAC Layer Errors: One of the main reasons for packet losses in wireless networks is due to MAC layer errors. The packets that cannot be transmitted due to excessive contention in the wireless medium and wireless channel errors are investigated using this performance metric. Along with the number of collisions, the MAC layer errors represent the local contention level around the sensor nodes. In our results, the percentage of total sent packets lost due to MAC layer errors are given to investigate the effect of MAC layer performance based on the traffic load.

Buffer Overflows: The memory limitations of the sensor nodes necessitate limited sized buffers to be used. As the network load increases, the packets are dropped due to excessive incoming traffic. The factors influencing this phenomenon are investigated through the percentage of the total sent packets lost due to buffer overflow. Moreover, the effect of the buffer size on the overall network performance is investigated.

End-to-end Latency: Several WSN applications such as tracking, intrusion detection and surveillance require that the observed event is reliably detected at the sink within a certain delay bound. Hence, the impact of various network characteristics such as sensor reporting rate, number of sources, buffer size, and contention window on the average end-to-end latency of data packets is also shown to study the tradeoffs related to latency.

Energy Efficiency: In WSN, energy efficiency of the developed protocols is also crucial due to the constrained energy resources of the sensors. Therefore, the average energy consumption per sent packet is also investigated.

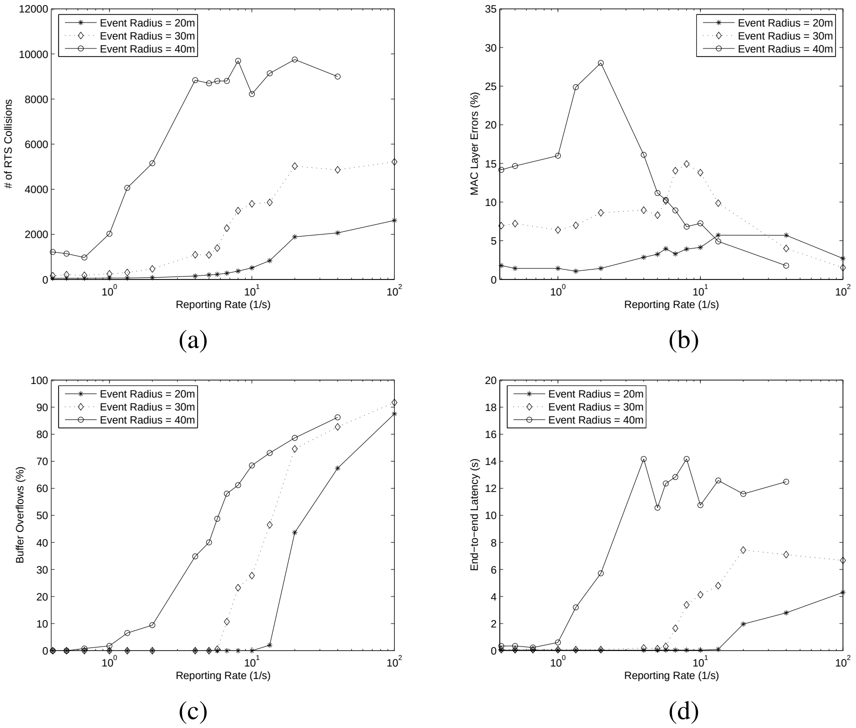
All above performance metrics help us to determine the interactions between the overall network congestion and local contention resolution mechanisms. In the following sections, we describe our comprehensive analysis, which reveals the effects of network parameters on congestion and contention in detail.

3 Analysis of Contention and Congestion in WSN

3.1 Effect of Number of Sources

In this section, the effect of traffic load on the network performance is investigated. As explained in Section 2, each sensor sends information to the sink if it is inside the event radius corresponding to an event generated randomly inside the sensor field. In order to present the effect of traffic load in a WSN, we performed simulations using various event radius values, i.e., 20m, 30m, and 40m.

The impact of number of sources on the overall event reliability is shown in Fig. 1. The *x*- and *y*-axes in Fig. 1 represent the reporting rate of the source nodes and the reliability, respectively. The reliability metric corresponds to the percentage of the total sent packets received at the sink throughout the simulation duration. As shown in Fig. 1, irrespective of the number of source nodes, the reliability remains constant when the report-



(a) (b)

(c) (d)

Figure 2. (a) Number of RTS collisions, (b) MAC layer errors, (c) Buffer overflows, and (d) End-to-end latency vs. reporting rate for different values of event radius.

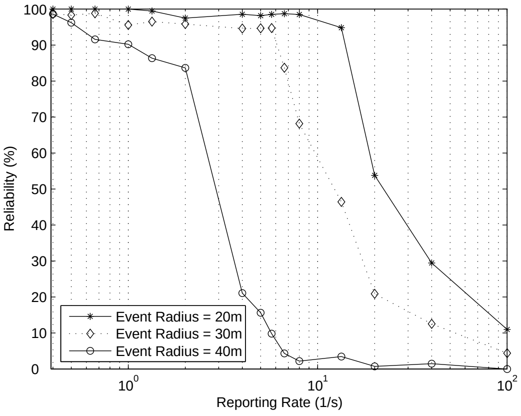


Figure 1. Reliability vs. reporting rate for different values of event radius.

ing rate is low and decreases sharply after a certain reporting rate. This decrease is also saturated as the reporting rate is further increased. This behavior is also observed throughout the results that will be presented in the following. For the sake of clarity in our discussions, here we introduce some definitions regarding this unique behavior in sensor networks.

We define two reporting rate thresholds, denoted as r_{th}^{low} and r_{th}^{high}, which represent the threshold for reporting rate when the network behavior is observed to change significantly. The actual values of these thresholds change based on the network configuration, such as number of source nodes, buffer length and number of maximum retransmissions. The first threshold, r_{th}^{low}, represents the reporting rate beyond which the network starts to be congested. As an example, r_{th}^{low} is found to be around $2s^{-1}$ for event radius of 20 m from Fig. 1. The region below r_{th}^{low}, where the event reliability is relatively constant, is referred to as the ***non-congested region***, since the buffer size of the nodes is enough to accommodate the traffic load. Beyond r_{th}^{low}, a sharp transition phase is observed, which is referred to as ***transition region***. This phase is where the network congestion builds up due to both traffic load increase and local contentions. Beyond a second threshold, r_{th}^{high}, the reliability saturates which is referred to as ***highly-congested region***. The discussions in the following will be based on these definitions.

As shown in Fig. 1, irrespective of the number of sources, highly-congested region is always observed. This is due to the excessive number of packets injected into the network which cannot be supported by the underlying wireless medium capacity. The reliability is kept at a reasonably high value, i.e., $R_{ev} > 85\%$, until r_{th}^{low}. However, as the reporting rate is increased beyond r_{th}^{high}, the reliability drops to significantly low values, i.e., $R_{ev} < 20\%$. It should be emphasized that the reliability graph shifts to left as the number of source nodes are increased, leading to lower r_{th}^{low} values. This is due to both increased number of packets injected into the network from increased number of sources and also due to higher contention experienced in the network. It is important to note that, the event reliability, R_{ev}, drops to 0 for the event radius of 40m at reporting rate $100s^{-1}$[1].

In order to investigate the reasons for the sharp decrease beyond r_{th}^{low}, we first present the number of RTS collisions and the percentage of MAC layer errors in Fig. 2(a) and Fig. 2(b), respectively. These figures clearly reveal the effect of increased network load on the local network channel contention. As shown in Fig. 2(a), the number of RTS collisions starts to increase below the r_{th}^{low} value when compared to Fig. 1. It is clear that local contention increases before the network is congested. However, through the contention resolution mechanism, this contention is controlled and the reliability is not affected. However, as the reporting rate is further increased, the increased contention leads to packet drops at the MAC layer as shown in Fig. 2(b). It is interesting to note that, the maximum values of the percentage of packet losses due to MAC layer errors correspond to the r_{th}^{low} values when compared to Fig. 1. Moreover, beyond this threshold, the percentage of MAC Layer errors starts to decrease. It is also important to note that as the number of source nodes increases, the maximum of the percentage of packet losses due to MAC layer errors occur at lower reporting rate values. This observation is also consistent with the event reliability observations shown in Fig. 1.

To further investigate the effect of number of source nodes on the overall network performance, the percentage of sent packets lost due to buffer overflow is shown in Fig. 2(c). These results show that buffer overflow is the major factor affecting the event reliability. Note that, the three regions, i.e., non-congested, transition and highly-congested regions are clearly observed from Fig. 2(c). When Fig. 2(a) and 2(b) are also considered, it can be observed that there is a close relation between buffer overflows and local contention. As the packets are dropped due to higher traffic load at the network buffer, the collisions and MAC layer errors start to saturate[2]. Since the node buffer is filled, MAC layer is supported with constant rate leading to saturation in local contention. As a result, it can be stated that network buffer size can control the saturated contention level in WSN. As the number of source nodes are increased, contention level is also increased. Since congestion builds up due to higher number of nodes sending information to the sink, the network is congested at lower reporting rates.

In Fig. 2(d), we have observed the average end-to-end latency of the event packets from sensor field to the sink node. As seen in Fig. 2(d), the average end-to-end packet latency is low in the non-congested region. Beyond r_{th}^{low}, the average packet latency starts to increase. This is obvious because the increased network load due to higher reporting rate leads to increase in the buffer occupancy and network channel contention. Thus, the average forwarding packet delay along the path from the sensors field to the sink node starts to increase. Note that the increase in the average packet delay is observed regardless of the number of source nodes and the increase in average packet latency occurs at higher reporting rates as the number of source nodes decreases.

Based on the results presented above, it can be stated that the number of sources in a WSN clearly affects the network performance. Especially higher number of source nodes leads to degradation in event reliability, congestion, local contention as well as end-to-end latency. However, more sources in the case of an event correspond to a spatial increase in the observed information, which may be crucial for the overall performance of the WSN application. Hence, the tradeoff between network performance and the application performance in terms of number sources should be carefully engineered.

3.2 Effect of Buffer Size

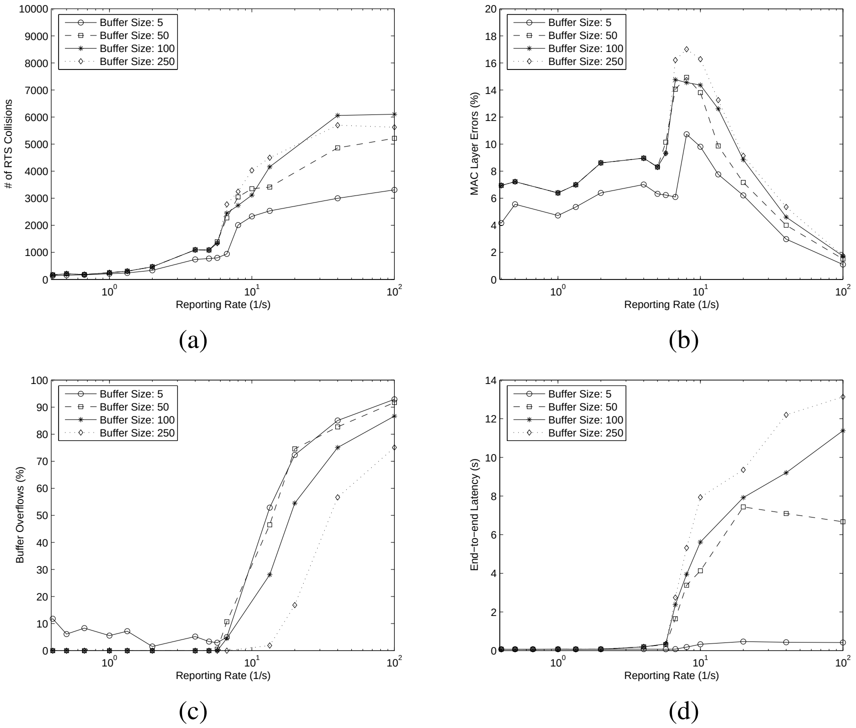
In this section, the impact of buffer size for the sensor nodes on the network performance is investigated. To this end, we performed simulations with different buffer sizes for the sensors, i.e., 5, 50, 100 and 250.

To investigate the effects of different buffer sizes of sensor nodes on the event reliability, in Fig. 3, we have observed the event reliability detected at the sink node for different buffer sizes of the sensors. It is clear that similar shape as observed in Fig. 1 is seen in Fig. 3. Moreover, the change in buffer size has minimal effect on the event reliability. Note that, as the network load increases, although the buffer size of the sensors is large, e.g., 250, event reliability cannot be provided due to the limited capacity of shared wireless medium. It is also important to note that when the buffer size is

---

[1] Since no packet is received by the sink at this point, it is not included in Fig. 2(a), 2(b), 2(c), and 2(d).

[2] Note that, in Fig. 2(b), the percentage of sent packets lost due to MAC layer errors is shown. Hence, the decrease in this value corresponds to a constant MAC layer error value.



(a) (b)

(c) (d)

Figure 4. (a) Number of RTS collisions, (b) MAC layer errors, (c) Buffer overflows, and (d) End-to-end latency vs. reporting rate for different retransmission limit values.

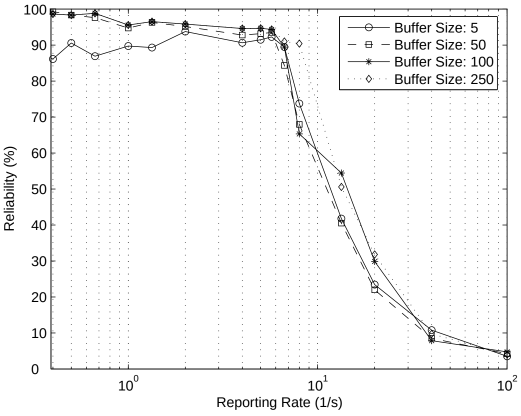


Figure 3. Reliability vs. reporting rate for different buffer sizes.

very small, i.e., 5, even for low reporting rates, event reliability can only be ensured to a certain extent, i.e., $R_{ev} \simeq 90\%$.

The number of RTS collisions and the percentage sent packets lost due to MAC layer errors are presented in Fig. 4(a) and Fig. 4(b), respectively. As shown in Fig. 4(b), for all buffer size values, the MAC layer errors increase sharply, when the critical reporting rate is reached. It is also interesting to note that after this critical reporting rate, the percentage of packet drops due to MAC layer errors starts to decrease[3]. This is due to the fact that when the network capacity is exceeded, the packet losses are mostly resulting from buffer overflows in the network as shown in Fig. 4(c).

Increasing buffer size in WSN has a negative effect on the local contention level as shown in Fig. 4(a) and Fig. 4(b). As the buffer size is increased, both the number of collisions and the percentage of sent packets lost due to MAC layer errors increase. The increase in collisions is due to increased number of packets waiting to be transmitted in each sensor node when the wireless channel capacity is exceeded. When the buffer size is low, these packets are already dropped and are not passed to the MAC layer, leading to lower contention. This interesting result is also evident from Fig. 4(c), where the percentage of sent packets lost due to buffer overflow is shown for different buffer sizes. Decrease in buffer size leads to increase in buffer overflows as

---

[3] In fact, when the network capacity is exceeded, the number of MAC layer errors becomes approximately constant which results in decrease in the percentage of packet drops due to MAC layer errors.

expected. As a result, the MAC layer errors decrease as shown in Fig. 4(b), which leads to the conclusion that lower buffer sizes can help decrease the local contention.

Another interesting tradeoff is observed when average end-to-end latency of the event packets from sensor field to the sink node is investigated. As seen in Fig. 4(d), the average end-to-end packet latency starts to increase as the reporting rate increases regardless of the buffer sizes. Note that decreasing the buffer size significantly decreases the end-to-end latency in the network. This is due to the fact that as the buffer size of the sensors increases, the queuing delay of the packets increases significantly. Moreover, for low buffer size values, buffer overflows lead to a larger number of packet losses in the network, which results in lower channel contention and lower end-to-end packet latency values compared to those values of higher buffer sizes.

As a result, the above discussions on the effects of buffer size reveal that, in the case of applications where event reliability can be afforded to be low, i.e., $R_{ev} \simeq 90\%$, and end-to-end latency is important, lower buffer sizes can be selected. This interesting result is contradictory to the conventional belief that limited storage capabilities of sensor nodes always leads to performance degradation. However, when coupled with the effect of local interactions, this property is shown to be advantageous for a specific class of applications.

3.3 Effect of MAC Layer Retransmissions

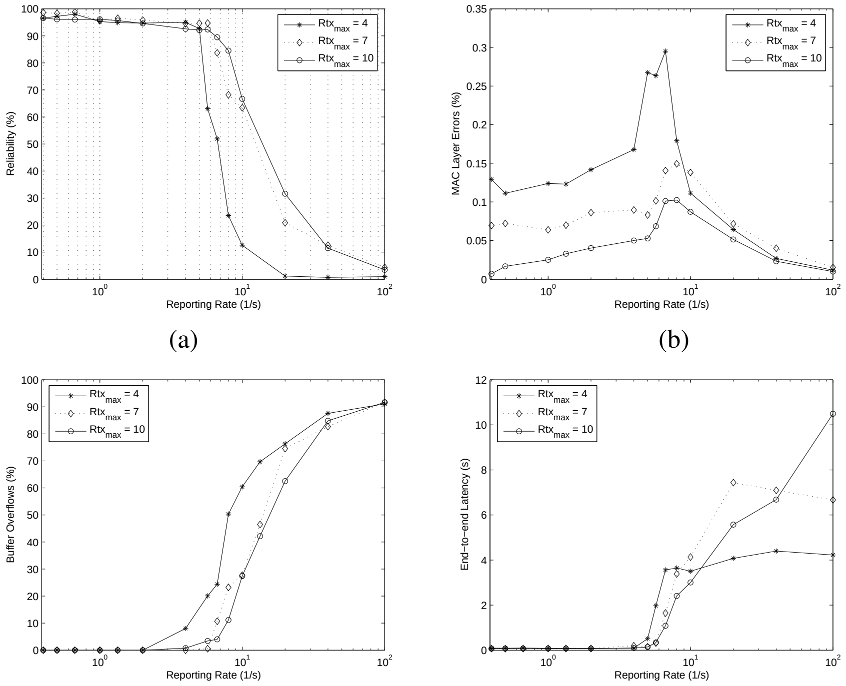
One of the main factors affecting the reliability in a multi-hop network is the local reliability mechanism which is implemented in the MAC layer. The MAC layer aims to provide hop-by-hop reliability by performing ARQ-based reliability mechanism. The performance of this mechanism mainly depends on the maximum number of retransmissions for packet failures. In this section, we investigate the effect of local reliability mechanism on the overall network performance. Moreover, we indicate interesting tradeoffs which occur due to the interaction of different mechanisms at different layers of the network stack.

In the following figures, we present the effect of maximum retransmission limit, Rtx_{max}, on the performance metrics introduced in Section 2. The results are shown for increasing Rtx_{max}, i.e., 4, 7, and 10.

The overall event reliability is shown in Fig. 5(a). The effect of hop-by-hop reliability is evident when the network is congested, i.e., reporting rate exceeds r_{th}^{high}. For lower values of Rtx_{max}, the event reliability begins to decrease at lower r_{th}^{low}. This decrease is also sharper when the local reliability is lower as shown with the $Rtx_{max} = 4$ graph. Note also that, although there exists significant difference between $Rtx_{max} = 4$ and $Rtx_{max} = 7$, further increase in the maximum retransmission limit to $Rtx_{max} = 10$ does not effect the overall network reliability significantly. Overall, the results show that by adjusting local reliability mechanism, higher reporting rates can be efficiently supported by the network.

To investigate the effects of maximum retransmission limit on the overall network performance, we also present the percentage of sent packets lost due to MAC layer errors in Fig. 5(b). As shown in Fig. 5(b), after a r_{th}^{low} value, for lower values of Rtx_{max}, we observe higher MAC layer drops in the network which leads to lower event reliability values for lower Rtx_{max}. Note that, after a r_{th}^{high} value, the percentage of MAC layer errors decreases sharply, since in this highly-congested region, packet drops occur due to buffer overflows irrespective of Rtx_{max} values. Consequently, when the network capacity is highly exceeded, in addition to local reliability mechanisms, end-to-end congestion control and reliability mechanisms should be performed to improve event reliability.

One of the tradeoffs in supporting higher reliability by adjusting the retransmission limit, Rtx_{max} is shown in Fig. 5(d). The latency trend in each of the three values for Rtx_{max} is composed of three phases. In the non-congested region, the end-to-end latency is in the range of 100 ms irrespective of the retransmission limit. Since the local contention level is low in this region, retransmission mechanism is not used. However, as the congestion level builds up, significant increase in the latency is observed. This increase is higher when higher Rtx_{max} is considered. More specifically, the increase in latency is due to increased contention level in the network and, consequently, the retransmissions that take place due to packet failures. In the highly-congested region, the latency is saturated. This is due to the buffer overflows at higher layers. Since these packets cannot reach the MAC layer, the end-to-end latency is kept at a relatively constant level. This interesting result is also evident from Fig. 5(c), where the percentage of sent packets lost due to buffer overflow is shown for different Rtx_{max} values. As shown in Fig. 5(c), after r_{th}^{high} value, irrespective of Rtx_{max} values, most of the packets are dropped due to buffer overflows before reaching the MAC layer which leads to above mentioned relatively constant latency in highly-congested region. Note that, retransmission limit Rtx_{max} has a negative effect on the saturated latency value. Since higher number of retransmissions are performed until a packet is eventually dropped, the latency saturates at a higher level. This shows a clear trade-off between event reliability and end-to-end latency when retransmission limit, Rtx_{max}, is considered.



(a) (b)

(c) (d)

Figure 5. **(a) Reliability, (b) MAC layer errors, (c) Buffer overflows, and (d) End-to-end latency vs. reporting rate for different retransmission limit values.**

3.4 Contention Window

As discussed in Section 3.3, local contention and hence collisions constitute one of the major sources for packet drops in WSN. Thus, contention resolution mechanisms are required in MAC protocols. In contention-based MAC protocols, the contention resolution mechanism is performed via contention window adjustments [3]. Each node determines its random backoff time, which is selected randomly between $(0, cw)$, where cw represents the contention window size. The contention window size, cw, is initially set to a minimum contention window size CW_{min}. Moreover, cw is increased as the contention level is increased in the vicinity of the node. Hence, the value of cw during the operation of a sensor node is representative of the local contention. In Fig. 6, the average cw value is shown. The average cw for two types of nodes in the WSN is presented in Fig. 6. These types of nodes are determined based on their roles in the transmission of event information. The nodes that generate the event information are referred to as *source nodes*, while the nodes that participate in forwarding the packets to the sink in the multi-hop network are referred to as *router nodes*.

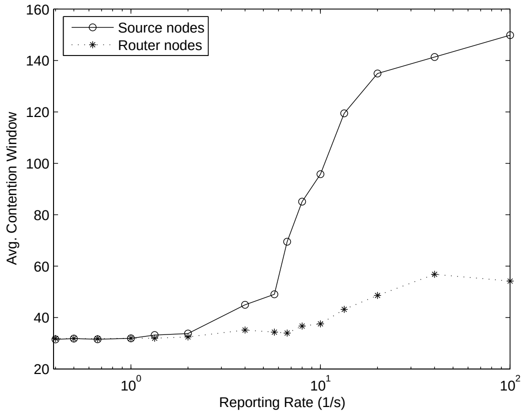


Figure 6. **Average contention window size for source nodes and router nodes.**

As shown in Fig. 6, average contention window size of the source nodes increases significantly in the transition region. An interesting result to note is that there is a huge difference between the average cw values for source and router nodes. This reveals that there is a high contention in the vicinity of source nodes, since multi-

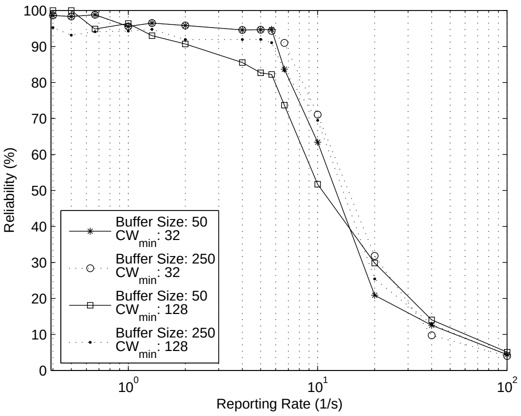


Figure 7. Reliability vs. reporting rate for different combinations of buffer size and contention window.

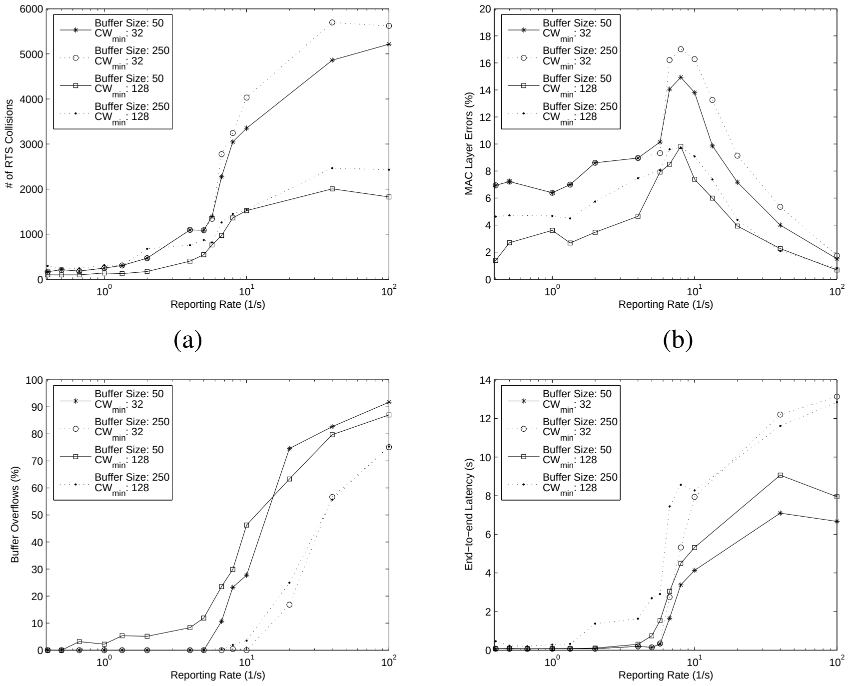
ple nodes try to send information about the same event at the same time. Moreover, as the reporting rate is increased, the average cw value increases. This implies that a higher cw value can be initially determined for applications that require higher reporting rate in order to increase the efficiency of the network.

In order to investigate the effect of initial contention window size, CW_{min}, on the network performance metrics, additional simulations are performed by varying the initial contention window size, CW_{min} and buffer size. In our simulations, the CW_{min} is first chosen as 32 which is the default value for IEEE 802.11 and then increased to 128 since this value is observed in Fig. 6 for high reporting rates which corresponds to the highly-congested region. Moreover, the buffer size is chosen as 50 and 250. In Fig. 7, the event reliability for 4 different combination of buffer sizes and CW_{min} values is shown. It is observed that when the reporting rate is very low, the event reliability is higher for lower CW_{min} value. The difference in reliability increases as the reporting rate is increased in the non-congested region. This is due to the unnecessary long contention window size at this region. However, in the transition region and the highly-congested region, the effect of using a higher CW_{min} is clearly seen. For lower buffer size, higher CW_{min} value leads to a maximum increase of 10% in reliability, in the highly-congested region. Moreover, if the event reliability curves for (Buffer Size, CW_{min}) values $(250, 32)$ and $(50, 128)$ are compared, it can be observed that similar reliability can be achieved in the highly-congested region. This reveals that, if the buffer size of the sensor nodes cannot be changed due to hardware constraints, the initial contention window size, CW_{min}, can be adjusted to achieve higher reliability for higher reporting rates.

The effect of initial contention window size CW_{min} on RTS collisions, MAC errors, and buffer overflows are shown in Fig. 8(a), 8(b), and 8(c), respectively. As shown in these figures, increasing CW_{min} has positive effect on MAC layer collisions and MAC layer errors. However, buffer overflows are mainly dependent on the buffer size, while interesting tradeoffs can be achieved based on the reporting rate as observed from the two solid curves in Fig. 8(c). It can be seen that for small buffer size and at higher reporting rates, higher initial contention window size decreases buffer overflows . The tradeoff in increasing the initial contention window size can be observed from Fig. 8(d), where the average end-to-end latency is shown. As the initial contention window size is increased, nodes backoff for a longer time in average. Hence, the end-to-end latency increases. Consequently, adaptive contention window mechanisms are required to improve overall network performance. It is clear that the existing contention resolution mechanisms adaptively increase the contention window size based on the local contention level. However, the knowledge of overall network condition changes such as an increase in the reporting rate can be exploited in the contention resolution mechanism to achieve higher efficiency.

3.5 Reasons for Packet Drops

In this section, we investigate the distribution of packet drops for different reporting rates. As shown in Fig. 9, the distribution of packet drops depends on the reporting rate. As explained in Section 3.1, the reporting rate determines the region the network is in. As the reporting rate is low, i.e., non-congested region, the packet drops are due to two sources: MAC layer failures, and routing layer failures. MAC layer failures consist of packet drops due to excessive number of unsuccessful retransmission attempts. Hence, the effect of wireless medium is also included. The routing layer failures are packet drops due to routing protocol timeouts, which occur when the next hop to the sink cannot be reached. It is observed that, in the non-congested region, the packet drops are mainly due to MAC layer errors. However, as the reporting rate increases, network congestion occurs since the wireless medium cannot support the injected load. As a result, buffer overflows start to dominate the packet drops. Note that, although the share of MAC failures in the overall packet drops decrease as the reporting rate is increased, the actual number of packet drops due to MAC failures remain constant. Hence, this constant value shows the limitations of the underlying wireless medium. The dynamic



(a)

(b)

(c)

(d)

Figure 8. (a) Number of RTS collisions, (b) MAC layer errors, (c) Buffer overflows, and (d) End-to-end latency vs. reporting rate for different combinations of buffer size and contention window.

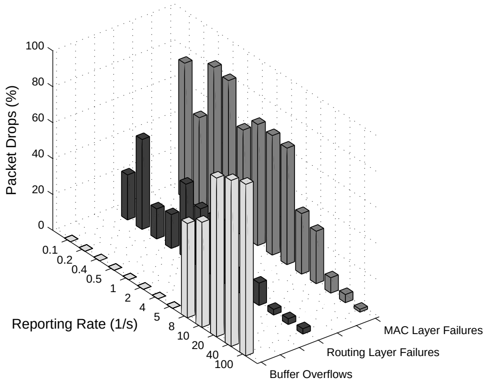


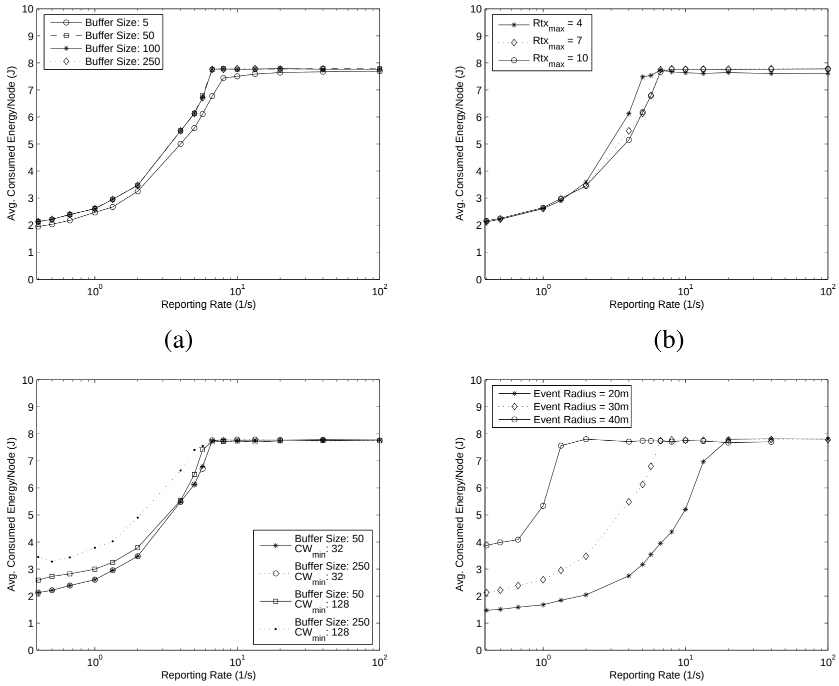
Figure 9. Distribution of packet drops due to buffer overflows, routing layer failures and MAC layer failures for different values of reporting rate.

change in packet drop distribution reveals that adaptive techniques for reliability mechanisms is required considering both the local and end-to-end reliability based on the traffic load in the network.

3.6 Energy Efficiency

In WSN, energy efficiency is crucial due to constrained energy resources of the sensors. The protocols should consider the energy efficiency in the network while accomplishing their application-specific objectives. Hence, the tradeoffs in energy consumption due to interactions among sensors is highly important to be investigated. Here, we provide insightful results for the effects of different network parameters, such as buffer size, MAC layer retransmission limit and event radius, on average energy consumption per sensor node.

The results of our simulations for different buffer sizes, Rtx_{max} values, initial contention window size CW_{min}, and event radius are shown in Fig. 10(a), 10(b), 10(c), and 10(d), respectively. In these plots, where the average energy consumption per node in the WSN is shown, an initial increase is observed as the reporting rate is increased. Moreover, a subsequent constant level of energy consumption is obtained above a certain a r_{th}^{low} value. Such a constant and saturated energy consumption is regardless of network parameters and is due to the limited capacity of the shared wireless medium. As the wireless medium capacity is saturated, the number of packets sent by the sensor nodes remains



(a) (b)

(c) (d)

Figure 10. **Average energy consumption per node for different (a) buffer size, (b) retransmission limit, (c) initial contention window size, and (d) event radius.**

constant leading to constant energy consumption. However, recall that the packets drops due to various reasons such as increased level of collisions or buffer overflows lead to inefficiency in the network although same energy consumption is observed.

In Fig. 10(d), the average energy consumption per node is shown for various event radius values. The event radius specifies the number of source nodes sending information about an event to the sink. As shown in Fig. 10(d), as the event radius increases, the r_{th}^{low} value, above which the energy consumption is saturated, occurs at lower reporting rate. This is due to the fact that as the event radius increases, the number of sources also increases. This results in network congestion and saturated energy consumption to start at lower reporting rates.

An interesting result obtained from Fig. 10(a) and 10(b) is that the average energy consumption per node is not significantly affected when the buffer length or the maximum retransmission limit is changed. However, as discussed in Section 3.2 and Section 3.3, these parameters have significant impact on network performance metrics. Hence, it is clear that buffer length and retransmission limit can be adjusted in WSN protocols according to the application specific requirements without hampering the energy consumption of the nodes. On the other hand, Fig. 10(c) reveals that, changing initial contention window size CW_{min} increases average consumed energy especially in the non-congested region. However, as discussed in Section 3.4, increasing initial contention window size is advantageous for higher reporting rates. This reveals that an adaptive solution for the initial contention window size is required to both achieve higher reliability and efficient energy consumption.

Overall, the careful adjustments in various network parameters such as buffer size, retransmission limit or contention window size can lead to efficient protocols in terms of event reliability or end-to-end latency. Therefore, the protocol parameters should be carefully determined based on the specifics of the applications.

4 Conclusion

In this paper, we investigated the interdependence between local contention and network-wide congestion through an extensive set of simulation experiments. The results of these experiments reveal interesting tradeoffs and interactions between different network parameters as summarized below:

- *Higher resolution vs. higher congestion:* In WSN, higher number of sources correspond to a spatial increase in the observed information, which may be crucial for the overall performance of the application. However, since the source nodes are potentially closely located, higher number of sources may result in increased contention. This in effect degrades the network performance. Hence, the tradeoff between network performance and the application performance in terms of number sources should be carefully engineered.

- *Small buffer size is more efficient:* For the applications which can afford low event reliability levels, i.e., $R_{ev} \simeq 90\%$, and end-to-end latency is important, lower buffer sizes lead to more efficient performance. Although may be contradictory to the conventional belief that limited storage capabilities of sensor nodes always leads to performance degradation, when coupled with the effect of local interactions, small buffer size is shown to be more efficient for a specific class of applications.

- *Local reliability is not sufficient for overall reliability:* Higher reporting rates can be supported by the network by adjusting local reliability mechanism. However, this in turn has a negative effect on the end-to-end latency. Moreover, when the network capacity is highly exceeded, in addition to local reliability mechanisms, end-to-end congestion control and reliability mechanisms should be performed to improve event reliability.

- *Traffic-aware contention window size adjustment is required:* Increasing initial contention window size leads to efficient event transport at high reporting rates. Hence, the knowledge of overall network condition changes such as an increase in the reporting rate can be exploited in the contention resolution mechanism to achieve higher efficiency. Moreover, if the buffer size of the sensor nodes cannot be changed due to hardware constraints, the initial contention window size can be adjusted to achieve higher reliability for higher reporting rates.

- *Adaptive cross-layer congestion control is necessary:* The dynamic change in packet drop distribution reveals that adaptive techniques for reliability mechanisms based on traffic load is required considering both the local and end-to-end reliability. However, such a requirement necessitates cross-layer design for efficient local contention resolution and event-to-sink congestion control.

- *Energy efficient adjustments are possible:* Average energy consumption per node is not significantly affected when the buffer length or the maximum retransmission limit is changed. Hence, it is clear that buffer length and retransmission limit can be adjusted in WSN protocols according to the application specific requirements without hampering the energy consumption of the nodes.

The results of our analysis reveals that local interactions between sensor nodes directly affects the overall performance. The interdependency between network parameters call for adaptive cross-layer mechanisms for efficient data delivery in WSN.

References

[1] I. Aad, and C. Castelluccia,“Differentiation Mechanisms for IEEE 802.11,” in *Proc. IEEE INFOCOM 2001*, pp. 209-218, Anchorage, AK, April 2001.

[2] O. B. Akan and I. F. Akyildiz, “ESRT: Event-to-Sink Reliable Transport for Wireless Sensor Networks,” in *IEEE/ACM Transactions on Networking*, October 2005, also in *Proc. ACM MOBIHOC 2003*, pp. 177-188, June 2003.

[3] IEEE 802.11, “Wireless LAN medium access control (MAC) and physical layer (phy) specifications,” 2001.

[4] I. F. Akyildiz, M. C. Vuran, O. B. Akan, and W. Su, “Wireless Sensor Networks: A Survey REVISITED,” *Computer Networks Journal (Elsevier)*, 2005.

[5] B. Hull, K. Jamieson and H. Balakrishnan, “Techniques for Mitigating Congestion in Sensor Networks,” in *Proc. ACM SENSYS 2004*, November 2004.

[6] S. McCanne and S. Floyd, ns Network Simulator, *http://www.isi.edu/nsnam/ns/*.

[7] S. Tilak, N. B Abu-Ghazaleh, and W. Heinzelman, “Infrastructure Tradeoffs for Sensor Networks,” in *Proc. ACM WSNA 2002,* pp. 49-58, September 2002, Atlanta, GA, USA.

[8] C. Y. Wan, S. B. Eisenman, and A. T. Campbell, “CODA: Congestion Detection and Avoidance in Sensor Networks,” in *Proc. ACM SENSYS 2003*, November 2003.

[9] A. Woo and D. E. Culler, “A Transmission Control Scheme for Media Access in Sensor Networks,” in *Proc. ACM MOBICOM 2001,* pp.221-235, Rome, Italy 2001.