Analysis of Congestion and Contention in Wireless Sensor and Actor Networks

V.C. Gungor [a,*] M.C. Vuran [a] O.B. Akan [b]

[a] *Broadband and Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332*

[b] *Department of Electrical and Electronics Engineering Middle East Technical University, Ankara, Turkey, 06531*

Abstract

Wireless Sensor and Actor Networks (WSAN) are composed of large number of sensor nodes collaboratively observing a physical phenomenon and relatively smaller number of actor nodes, which act upon the sensed 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 multi-hop nature of WSAN entangles the level of local contention and the experienced network congestion. Therefore, the unique characteristics of WSAN necessitate a comprehensive analysis of the network congestion and contention under various network conditions. In this paper, we comprehensively investigate the interactions between contention resolution and congestion control mechanisms as well as the physical layer effects in WSAN. 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 the interdependency between network parameters call for adaptive cross-layer mechanisms for efficient data delivery in WSAN.

Key words: Wireless sensor and actor networks, congestion detection and control, cross-layer design.

* Corresponding author. Tel: (404) 894-6616; Fax: (404) 894-7883
Email addresses: gungor@ece.gatech.edu (V.C. Gungor), mcvuran@ece.gatech.edu (M.C. Vuran), akan@eee.metu.edu.tr (O.B. Akan).

1 Introduction

Wireless Sensor and Actor Networks (WSAN) are composed of large number of sensor nodes collaboratively observing a physical phenomenon and relatively smaller number of actor nodes which act upon the sensed phenomenon [3]. Multiple sensor nodes communicate their measurements of the observed physical phenomenon in a multi-hop manner (i) either to the sink, which, in turn, decides on the event [1] and sends the action commands to the actor node(s), or (ii) directly to the actor nodes, in a coordinated way, which performs both decision and action upon the sensed phenomenon.

Due to the memory restrictions of the sensor nodes and limited capacity of shared wireless medium, network congestion can be experienced during the operation of the network. 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 [4], [6]. 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 WSAN applications demand.

Unlike the congestion cases in conventional wired networks, many potential reasons may lead to overall network congestion in WSANs. Communication in a shared wireless medium in WSANs constitutes one of the main sources of congestion, which has not been considered in conventional congestion control approaches. Moreover, the multi-hop nature of the WSAN amplifies the likelihood as well as the severity of network congestion. In general, the main sources for network congestion in WSANs can be classified as follows:

- *Channel Contention and Interference:* In WSANs, the local channel contention in the shared communication medium may result in network congestion. This channel contention can occur between different flows passing through the same vicinity and between different packets of the same flow. Consequently, the outgoing channel capacity of a sensor node becomes time-variant. This, in turn, makes the node's congestion level oscillating and unpredictable even in case of constant incoming traffic rate. Moreover, high density of sensor nodes in densely deployed WSAN scenarios exacerbates the impact of the channel contention.
- *Number of Event Sources:* WSANs are specialized in informing events observed by the sensor nodes and acting upon the observed event by the actor nodes. Hence, the number of nodes transmitting event features directly affects both the efficiency of the network protocols and the accuracy of the event information [7]. Although higher number of event sources can improve the accuracy of the event information, the multi-hop nature and the local

[1] The distinct changes in the physical phenomenon are referred to as *events* in WSAN.

interactions between sensor nodes can degrade the overall network performance.

- *Packet Collisions:* High network contention increases the probability of packet collisions in the wireless medium. Based on the underlying medium access control (MAC) mechanism, after several unsuccessful transmission attempts, these packets are dropped at the sender node. Hence, the decrease in buffer length due to these drops may inaccurately indicate lower congestion when only buffer length is considered for congestion detection. Therefore, for accurate congestion detection in WSANs, a hybrid approach is required.
- *Reporting Rate:* Mainly, WSAN applications can be classified into two classes, i.e., event-driven and periodic [3]. In event-driven applications, the reporting rate of sensor nodes can change during the lifetime of the network. Whereas, for applications with periodic traffic, the reporting rate must be controlled for the proper operation of the network. In both cases, as a result of increased reporting rate, network congestion occurs even if local contention is minimized. This conventional reason for network congestion has a different meaning in WSAN since the sink (or the actor node based on the assumed WSAN architecture [3]) is interested only in the collective information from multiple sensors rather than individual flows. Therefore, a collaborative approach is required in controlling flow rates.
- *Many to One Nature:* Due to the collaborative nature of the WSANs, the packet transmission about an event from multiple sensors to few number of actor nodes or to a single sink (depending on the WSAN architecture assumed [3]) may create a bottleneck, especially around the receiving architectural element (sink or the actor node). Hence, this many-to-one nature also creates congestion in the network.

The reasons for congestion in WSANs, 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 [8],[14]. Therefore, it is also clear that the channel conditions and physical layer effects are also important factors which may affect the contention, congestion levels and hence the overall network performance [3], [12].

Majority of the congestion control algorithms proposed for sensor networks [2],[8],[14] state that cross-layer interactions between transport layer and MAC layer is imperative for efficient congestion detection and hence congestion control in multi-hop sensor networking paradigm. In [14], channel load information from the MAC layer is incorporated into congestion detection and control mechanisms. In a converse approach, the authors in [15] transmission control scheme for use at the MAC layer in WSN is proposed. 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, [8] 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 [8] that MAC layer support is beneficial in congestion detection and control algorithms.

In [16], the analysis of the relation between channel contention and network congestion has been performed for wireless sensor networks with the assumption that the sensor nodes send their readings to a single sink, which clearly does not apply to WSANs. Therefore, this analysis do not consider the coexistence of sensor and actor nodes as well as the effects of having multiple actors, all of which are to receive data from sensor nodes. Furthermore, the analysis in [16] does not also investigate the effects of physical layer issues on the local contention and network congestion in WSAN.

Overall, it is clear that cross layer approaches in congestion detection and control is necessary in WSAN due to the tight relation between local contention and network-wide congestion. Despite the considerable amount of research on several aspects of congestion control in sensor networks, the interdependence of congestion and contention in WSAN are yet to be efficiently studied and addressed. Therefore, the unique characteristics of WSAN call for a comprehensive analysis of the network congestion and contention under various 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 WSANs?*
- *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?*
- *What are the effects of physical layer issues on channel contention and network congestion?*
- *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 actors, number of sources, buffer size, MAC layer

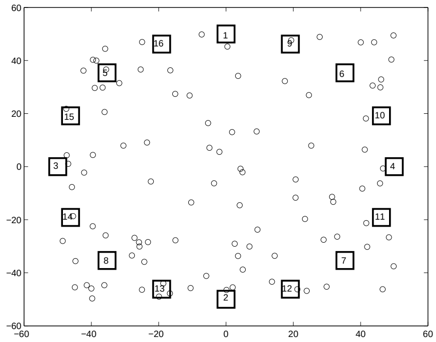

Fig. 1. **Sample topology used in the simulations. The circles represent the sensors while the squares represent the actors. The number of an actor is also shown.**

retransmissions, contention window, and physical layer parameters on various network performance metrics are investigated in Sections 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, respectively. Moreover, the reasons for packet drops and the effects on energy efficiency is explored in Sections 3.7 and 3.8. Based on these discussions, the paper is concluded in Section 4 along with possible approaches for efficient event communication in WSAN.

2 Overview

The goal of our work is to investigate the interactions between local contention and network-wide congestion in WSANs. 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* [10]. The simulations are performed using this environment in a 100x100m^2 sensor field. 100 sensors are randomly deployed in this field. Moreover, 16 actors are placed evenly on a circle of radius 50m. A sensor node transmits its information to the closest actor when an event occurs in its sensing range. A sample network topology is shown in Fig. 1, while the parameters used in the simulations are shown in Table 2. Unless otherwise specified in the paper, these parameters are used in the simulations. We vary the number of actors that are active to illustrate the effect of number of actors collecting an information. The number of actors are selected as 1, 2, 4, 8, and 16 and their locations are indicated by their numbers in Fig. 1. In each simulation, events are generated at the center of the topology and nodes inside a certain event radius, R_{ev}, become source nodes and start to send information to the actors. During the simulations, the locations of the actors are fixed and 5 different topologies with random sensor placement are used. The results are the average of these simulations.

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	100 s

Table 1
NS-2 simulation parameters

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

Event Reliability (ER_{ev}): WSAN 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 WSAN. We define the reliability as the percentage of total sent packets that are received at the actor nodes.

Collisions: The performance of the WSAN 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 represent 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 WSAN applications such as tracking, intrusion detection and surveillance require that the observed event is reliably detected at the actor 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 WSANs, 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

3.1 Effect of Number of Actors

In this section, the effect of number of actors that collect information from sensors is investigated. As explained in Section 2, each sensor sends information to the closest actor if it is inside the event radius corresponding to an event generated randomly inside the sensor field. Increasing the number of actors that collect this information disperses the traffic from the event area to multiple directions. This dispersion may lead to less congestion in the WSAN. However, since more sensor nodes are used for routing traffic from multiple sensors, the energy consumption may increase if too many actors are used. Our investigations show that there is a tradeoff in the number of actors and an arbitrary number may lead to performance degradation when compared to single sink topologies. In order to present the effect of number of actors, we performed simulations for various number of actors, i.e., 1, 2, 4, 8, 16, that are evenly located around a circle of radius 50m.

The impact of number of actors on the overall event reliability is shown in Fig. 2. The x- and y-axes in Fig. 2 represent the reporting rate of the source nodes and the reliability, respectively. The reliability metric corresponds to the

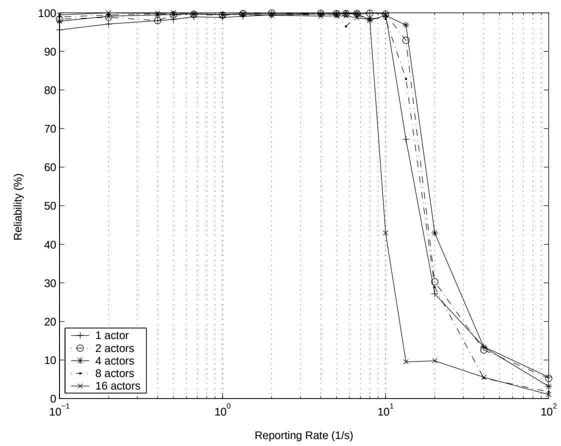

Fig. 2. **Reliability vs. reporting rate for different number of actors.**

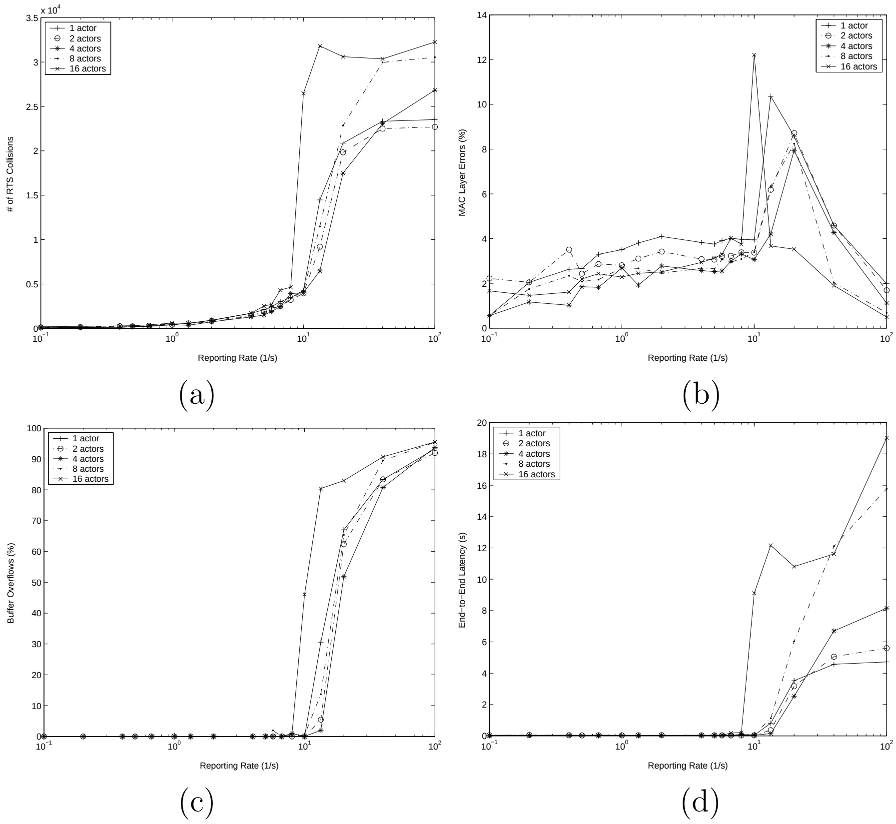

Fig. 3. **(a) Number of RTS collisions, (b) MAC layer errors, (c) Buffer overflows, and (d) End-to-end latency vs. reporting rate for different number of actors.**

percentage of the total sent packets received at all the actors throughout the simulation duration. As shown in Fig. 2, irrespective of the number of actors, the reliability is almost 100% when the reporting rate is low and decreases sharply above 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 WSANs.

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 actors and source nodes, buffer length and the maximum retransmission limit. The first threshold, r_{th}^{low} represents the reporting rate above which the network congestion starts to build up. As an example, r_{th}^{low} is found to be around $8s^{-1}$ when 16 actors collect information from the sensor nodes from Fig. 4. The region below r_{th}^{low} where the event reliability is relatively constant is referred to as the ***non-congested region***. This regime, the buffer occupancy of the nodes is low enough that the traffic load is accommodated without causing congestion. Above r_{th}^{low}, a sharp transition phase is observed which is referred to as the ***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***. Similarly, r_{th}^{high} is found to be $13s^{-1}$ for 16 actors. The discussions in the following will be based on these definitions.

As shown in Fig. 2, irrespective of the number of actors, 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 fairly high value, i.e., $ER_{ev} >$ 95%, while $r > r_{th}^{low}$. However, as the reporting rate, r, is increased above r_{th}^{high}, the reliability drops to significantly low values, i.e., $ER_{ev} <$ 10%. The number of actors affect this behavior, by shifting the reliability-reporting rate graph to left or right. It can be observed that there is an optimal number for actors that should collect sensor information that maximizes the reliability. In our experiments, this value is found to be 4. It is observed that when the number of actors is increased from 1 to 4, the reliability graph shifts to right, which results in higher r_{th}^{low} and r_{th}^{high} values. As a result, the network can be operated at higher reporting rates without affecting the reliability of the network. Higher reporting rates may lead to higher resolution for event estimation at the actors and more accurate actions being taken. However, increasing the number of actors beyond this point has adverse affects on reliability. As an example, reliability drops by 85%, when the number of actors is increased from 4 to 16 at $r = 13s^{-1}$.

In order to further investigate the reasons for the sharp decrease beyond r_{th}^{low} and the effect of number of actors, we first present focus on local interactions of the sensor nodes. For this purpose, the number of RTS collisions and the percentage of MAC layer errors are shown in Fig. 3 (a) and Fig. 3 (b), respectively. These figures clearly reveal the effect of increased network load on the local channel contention. As shown in Fig. 3 (a), the number of RTS collisions starts to increase at a lower reporting rate than the r_{th}^{low} value found in Fig. 2. This shows that the local contention increases before the network is congested. However, through the contention resolution mechanism, this contention is controlled and the reliability is not affected up to some point. Whenever the reporting rate is further increased, the increased contention leads to packet drops at the MAC layer as shown in Fig. 3 (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. 2. Moreover, above this critical reporting rate, the percentage of packet drops due to MAC layer errors starts to decrease [2]. 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. 3 (c). It is also important to note that as the tradeoff caused by number of actors is still evident here. 16 actors cause the most number of RTS collisions when compared to other values for actors. This is mainly due to the fact that multiple routes need to be constructed to reach each of the actors. Since more nodes participate in routing when the number of actors is increased, these nodes cause contention among each other. While dispersing the traffic to multiple actors minimize the congestion, the contention is increased due to the local interactions of these multiple routes to the actors.

To further investigate the effect of number of actors on the overall network parameters, the percentage of sent packets lost due to buffer overflow is shown in Fig. 3 (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 also from Fig. 3 (c). When Fig. 3 (a) and Fig. 3 (b) are also considered, we observe 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 [3]. 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 WSAN. As the number of actors is increased to 4, buffer overflows are decreased leading to higher reliability. Since congestion is controlled by dispersing the traffic to multiple actors, the network is congested at higher reporting rates. However, increasing the number of actors above 4 leads to higher percentage of buffer overflows than observed by the single actor

[2] 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.

[3] Note that, in Fig. 3 (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.

scenario.

In Fig. 3 (d) we show the average end-to-end latency of the event packets from sensor field to the actors. As seen in Fig. 3 (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 actor node starts to increase. Moreover, increasing collisions lead to retransmissions, which also increase the MAC layer delay. Note that, the increase in the average packet delay is observed regardless of the number of actors.

Based on the results presented above, it can be stated that selecting the number of actors in a WSAN significantly affects the network performance. The performance results show that an optimal number of actors is necessary for efficient communication and increasing the actors above this number leads to degradation in overall network performance. Especially higher number of actors leads to degradation in event reliability, congestion, local contention as well as end-to-end latency. In our experiments, we have found that 4 actors leads to the best performance among other number of actors. Hence, in the following, we present the results for 1 and 4 actors to investigate the various factors that affect the performance of WSANs.

3.2 Effect of Number of Sources

The network congestion and local contention is directly related to the traffic in the network. As discussed in the previous section, reporting rate of sensor nodes is one of the factors that influence the network traffic. In addition to the reporting rate of a sensor node, the number of sensors that report their observations to their associated actors is also a major factor. In this section, we investigate the effect of this factor on various network performance metrics. As explained in Section 2, each sensor sends information if it is inside the event radius corresponding to an event. In order to present the effect of number of source in a WSAN, we performed simulations using various event radius, R_{ev}, values, i.e., 20m, 30m, and 40m. In each figure results for 1 and 4 actors are shown.

The impact of number of sources on the overall event reliability is shown in Fig. 4. A similar trend as discussed in Section 3.1 is also observed irrespective of the number of source nodes. Moreover, the reliability-reporting rate graph shifts to left as the number of source nodes are increased, leading to lower r_{th}^{low} values. The reasons for this shift is twofold. First reason is the increased

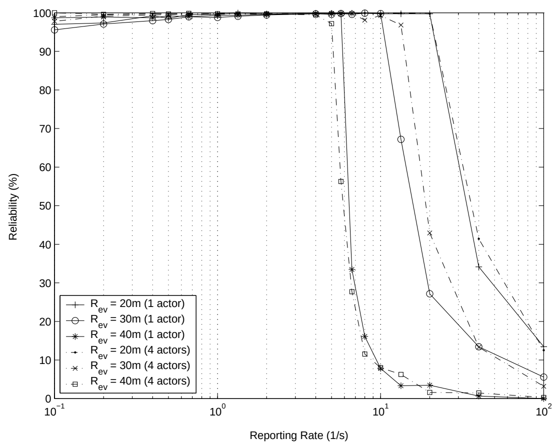

Fig. 4. **Reliability vs. reporting rate for different values of event radius, R_{ev}.**

number of packets injected into the network because of the increased number of sources. Second, higher contention is experienced in the network since more nodes contend to send their information. An interesting result is the effect of number of actors when the event radius is changed. for $R_{ev} < 40$m, 4 actors result in higher reliability values in the transition region and the network congestion is observed at higher reporting rates. However, for $R_{ev} = 40$m, increasing the number of actors slightly increases congestion. This important result is due to the effect of contention as we will investigate next.

In Fig. 5 (a) and Fig. 5 (b), we present the number of RTS collisions and the percentage of MAC layer errors, respectively. These figures clearly reveal the effect of increased network load on the local network channel contention. It is observed 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. 4. Moreover, the reason for lower reliability for $R_{ev} = 40$m with 4 actors can be seen in Figure 5 (b). MAC errors constitute a higher percentage of sent packets since higher number of routes are generated and more nodes contend for access to the medium when the number of actors is increased.

To further investigate the effect of number of source nodes on the overall network parameters, the percentage of sent packets lost due to buffer overflow is shown in Fig. 5 (c). 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 actor, the network is congested at lower reporting rates. In Fig. 5 (d) we present the average end-to-end latency of the event packets from sensor field to the actor node. 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

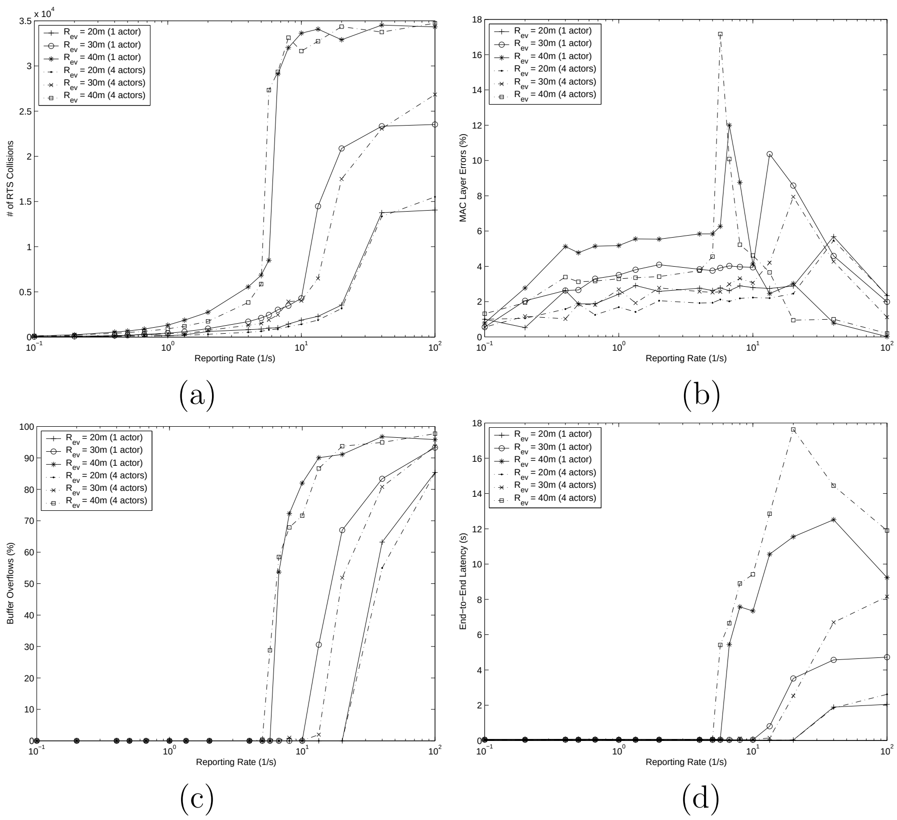

Fig. 5. **(a) Number of RTS collisions, (b) MAC layer errors, (c) Buffer overflows, and (d) End-to-end latency vs. reporting rate for different values of event radius, R_{ev}.**

number of source nodes decreases. An interesting result is that in the congested region, the latency for 4 actors is higher than 1 actor. Although distributed event transmission is assumed to decrease end-to-end latency, this is not the case when network is congested. However, it is important to note that in the transition region, the latency for 4 actors is slightly less than the case for 1 actors for $R_{ev} < 40$m. This result motivated the need for multiple actors in an event area since non-congested and transition regions are of interest for practical operation.

Based on the results presented above, it can be stated that the number of sources in a WSAN 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 accuracy of event estimation and timeliness of actions for the WSAN application. Hence, the tradeoff between network performance and the application performance in terms of number of sources should be carefully engineered.

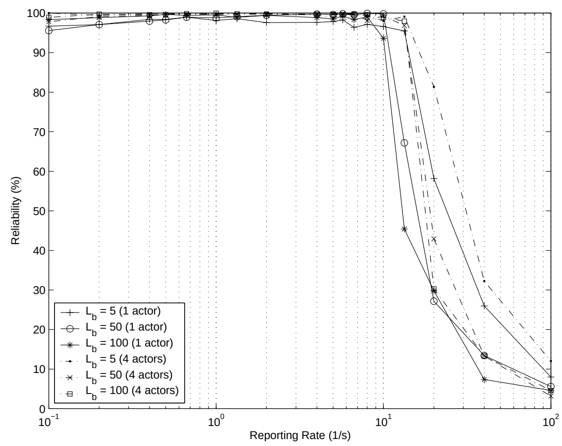

Fig. 6. **Reliability vs. reporting rate for different values of buffer length.**

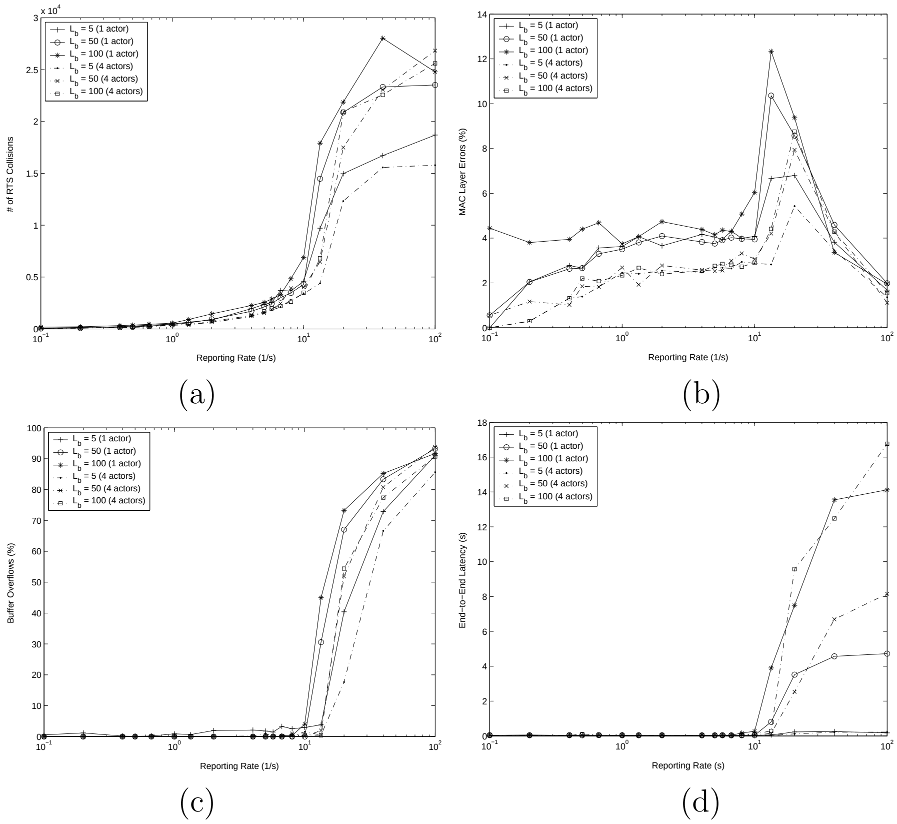

Fig. 7. **(a) Number of RTS collisions, (b) MAC layer errors, (c) Buffer overflows, and (d) End-to-end latency vs. reporting rate for different values of buffer length.**

3.3 Effect of Buffer Size

In this section, the impact of buffer size for the sensor nodes on the network performance is investigated. For this purpose, we performed simulations using different buffer sizes, L_b, for the sensors, i.e., 5, 50, and 100.

To investigate the effects of different buffer sizes of sensor nodes on the event reliability, in Fig. 6, we have observed the event reliability for different buffer sizes of the sensors for 1 and 4 actors. It is clear that similar shape as observed in Fig. 4 is seen in Fig. 6. 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., 100, the event reliability cannot be provided due to the limited capacity of shared wireless medium. It is also important to note that increasing the number of actors to 4 improves the reliability especially when the buffer length, L_b is small.

Increasing buffer size in WSAN has a negative effect on the local contention level as shown in Fig. 7 (a) and Fig. 7 (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. 7 (c), where the percentage of sent packets lost due to buffer overflow is shown for different buffer sizes and number of actors. When the reporting rate is low, a decrease in buffer size leads to increase in buffer overflows as expected. However, in the transition region, lower buffer sizes lead to lower buffer overflows. As a result, the MAC layer errors decrease as shown in Fig. 7 (b), which leads to the conclusion that lower buffer sizes can help decrease the local contention. Furthermore, increasing the number of actors also positively influence the buffer overflow performance of WSANs.

Another interesting tradeoff is observed when average end-to-end latency of the event packets from sensor field to the actor node is investigated. As seen in Fig. 7 (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. Finally, increasing the number of actors increase the end-to-end latency in the congested region, as expected according to the previous discussions.

As a result, the above discussions on the effects of buffer size reveals that, in the case of applications where event reliability can be afforded to be low, i.e., $ER_{ev} \simeq 90\%$, 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.

3.4 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. In the following figures, we present the effect of maximum retransmission limit, Rtx_{max}, on the network performance metrics introduced in Section 2. The results are shown for Rtx_{max} values of 4, 7, and 10. It is clear that increasing the retransmission limit results in more reliable links being established. On the other hand, since retransmissions increase the MAC layer delay, buffer overflows and end-to-end latency may increase. Accordingly, we indicate interesting tradeoffs which occur due to the interaction of different mechanisms at different layers of the network stack.

The overall event reliability is shown in Fig. 8 (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 supported by the network efficiently. Another way to improve the network reliability when local reliability is low is to increase the number of actors. The reliability graphs for 4 actors result in higher r_{th}^{low} values. However, the effect of retransmission limit is more important when the curves for $Rtx_{max} = 4$ (4 actors) and $Rtx_{max} = 7$ (1 actors) are compared. A higher retransmission limit leads to higher reliability even though a single actor is used for data collection.

To investigate the effects of maximum retransmission limit on the overall network performance, we also present number of RTS collisions in Fig. 8 (b). As shown in Fig. 8 (b), for lower values of Rtx_{max}, we observe higher MAC layer drops in the network in the transition and congested regions, which leads to lower event reliability 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.

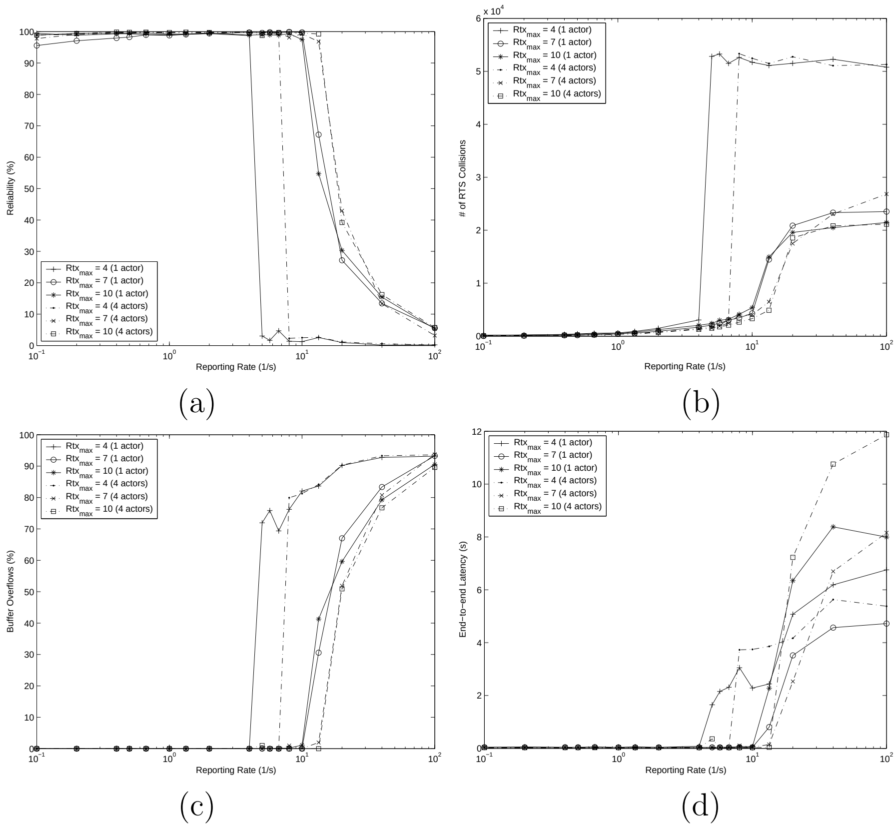

Fig. 8. **(a) Reliability, (b) number of RTS collisions, (c) buffer overflows, and (d) end-to-end latency vs. reporting rate for different values of retransmission limit, Rtx_{max}.**

One of the tradeoffs in supporting higher reliability by adjusting the retransmission limit, Rtx_{max} is shown in Fig. 8 (d), where the end-to-end latency is shown. 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 starts at lower reporting rate values when Rtx_{max} is small. 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. 8 (c), where the percentage of sent packets lost due to buffer overflow is shown for different Rtx_{max} values. As shown in Fig. 8 (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. Increasing the number of active actors in the event area also increases the end-to-end latency irrespective of the retransmission limit. This effect, however, is high for higher retransmission limit values.

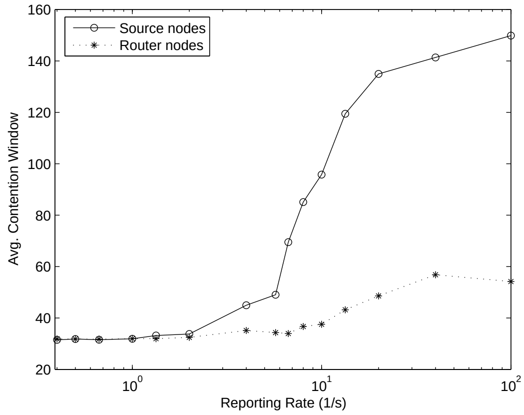

Fig. 9. **Average contention window size for source nodes and router nodes.**

3.5 Contention Window

As discussed in Section 3.4, 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 [9]. 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. 9, the average cw values two types of sensor nodes in the WSAN are presented. 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 actor in the multi-hop network are referred to as *router nodes*.

As shown in Fig. 9, 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 multiple 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, we performed simulations by varying

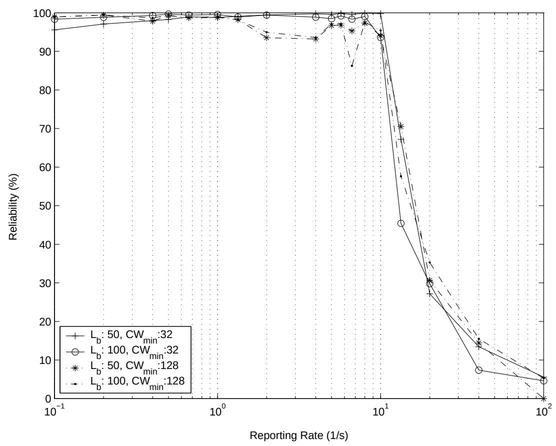

Fig. 10. **Reliability vs. reporting rate for different combinations of buffer size and contention window.**

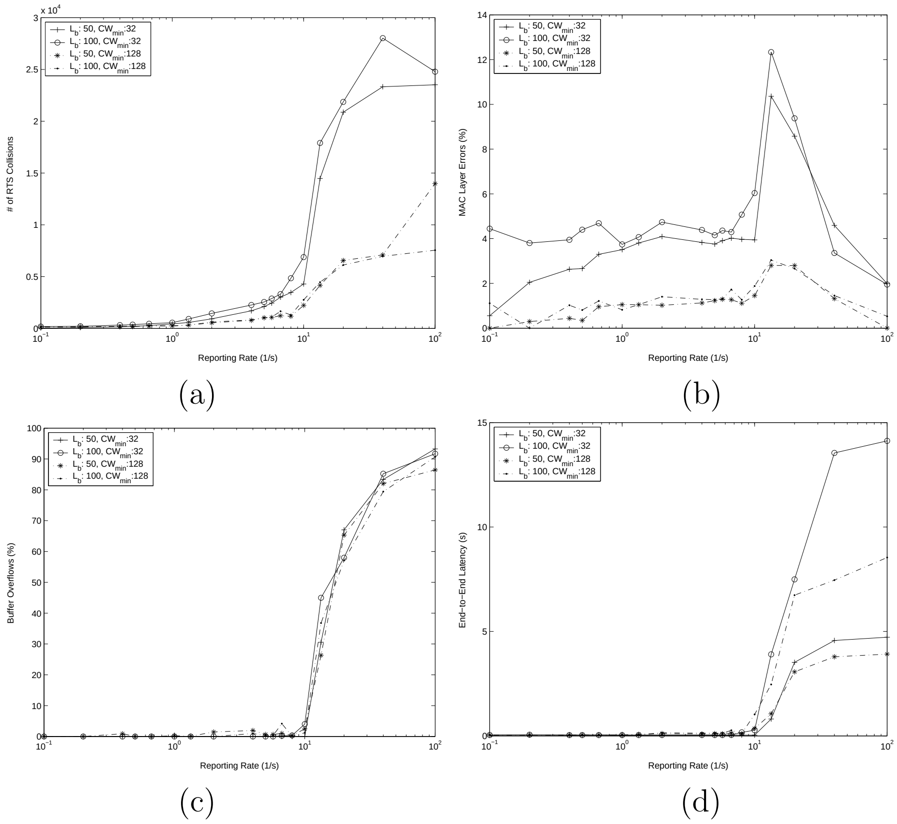

Fig. 11. **(a) Number of RTS collisions, (b) MAC layer errors, (c) Buffer overflows, and (d) End-to-end latency vs. reporting rate for different combinations of buffer size and contention window.**

the initial contention window size, CW_{min} and buffer size. In our simulations, the CW_{min} is first chosen as 32 and then increased to 128 since this value is observed in Fig. 9 for high reporting rates. Moreover, the buffer size is chosen as 50 and 100. Since the number of actors play a similar role as explained in the previous discussions, we do not include them in this section for space considerations.

In Fig. 10, 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 the unnecessary long contention window size at this region. However, in the transition region and the highly-congested region, similar values are observed.

The effect of initial contention window size CW_{min} on RTS collisions, MAC errors, and buffer overflows are shown in Fig. 11 (a), 11 (b), and 11 (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 generally independent of the initial contention window size. Another advantage of increasing the initial contention window size can be observed from Fig. 11 (d), where the average end-to-end latency is shown. Higher initial contention window size results in slightly higher latency in the transition region while it decreases the end-to-end latency in the congested region. This is explained by Fig. 11 (a) and 11 (b). Since higher contention window size decreases collisions, less number of retransmissions is required for successful delivery of packets. As a result, the access delay is reduced resulting in lower end-to-end latency. However, higher contention window size leads to higher backoff durations. As a result, the buffer overflows are not affected. 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 can also be exploited. For example an increase in the reporting rate can be exploited in the contention resolution mechanism to achieve higher efficiency.

3.6 Wireless Channel Effects

When a radio signal propagates through the wireless environment, it is affected by reflection, diffraction and scattering [12]. In addition to these, in WSANs, low antenna heights of the sensor nodes (10s of cms) and near ground communication channels cause signal distortions due to ground reflection. In this section, we investigate the effects of wireless channel on network congestion and channel contention in terms of event reliability and latency. For this purpose, we model a realistic physical layer using log-normal shadowing path loss model [12]. This model is used for large and small coverage systems and moreover, experimental studies have shown that it provides more accurate multi-path channel models than Nakagami and Rayleigh models for indoor

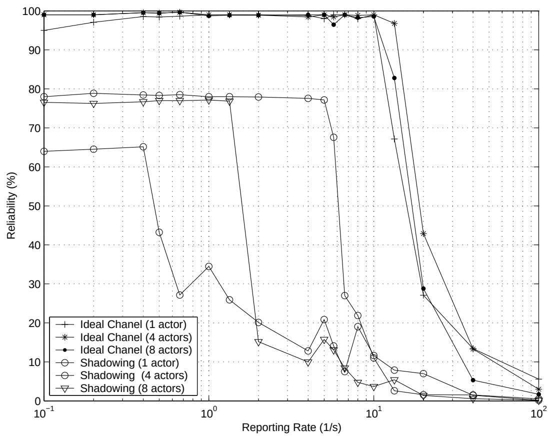

Fig. 12. **Reliability vs. reporting rate in case of realistic wireless channel.**

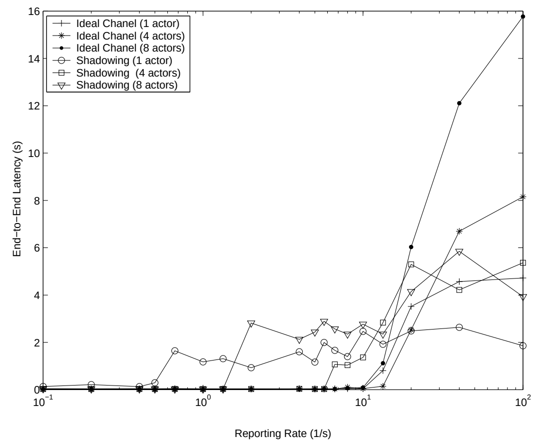

Fig. 13. **End-to-end latency vs. reporting rate in case of realistic wireless channel.**

wireless environments with obstructions [11], [17]. In this model, the signal to noise ratio $\gamma(d)$ at a distance d from the transmitter is given by:

$$\gamma(d)_{dB} = P_t - PL(d_0) - 10\eta log_{10}\Big(\frac{d}{d_0}\Big) - X_\sigma - P_n \quad (1)$$

where P_t is the transmit power in dBm, $PL(d_0)$ is the path loss at a reference distance d_0, η is the path loss exponent, X_σ is a zero mean Gaussian random variable with standard deviation σ, and P_n is the noise power in dBm. In practice, the values of path loss exponent (η) and the standard deviation (σ) are computed from experimentally measured data. For example, η is 2 to 3 for indoor environments with obstructions and σ ranges from 2 to 5 based on different environment characteristics [12] and [17]. [4]

[4] In our simulation experiments, we have used η=3.0 and σ=3.8, which are typical values found by experiments in [17] for indoor environments.

In Fig. 12, we have shown the impact of the number of actors and the realistic wireless channel on the overall event reliability. As shown in Fig. 12, irrespective of the number of actors and wireless channel model, the event reliability remains approximately constant, when the reporting rate is low and decreases sharply after a certain reporting rate. This behavior is similar to the event reliability observations presented in Section 3.2. Note that, when a realistic wireless channel is taken into account, 100% event reliability cannot be provided due to adverse wireless channel effects even if network load is very low. Therefore, in WSANs, to provide application specific reliability requirements, channel coding and transport layer reliability mechanisms are required in addition to efficient congestion control algorithms. Furthermore, in Fig. 12, when the number of actors in the deployment field is increased, it is observed that the network experiences congestion in higher reporting rates compared to single actor scenarios. This is because in multiple actor cases, network load is distributed among actor nodes and thus, network resilience against congestion and contention is increased, leading to high values of r_{th}^{low}.

In Fig. 13, we also observe the average end-to-end latency of the event packets when the realistic wireless channel is modelled. As shown in Fig. 13, the average packet latency is low in the non-congested region for both single actor and multiple actor scenarios. Beyond r_{th}^{low}, the packet latency starts to increase. This behavior 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 actor node starts to increase. This observation is also consistent with the end-to-end latency observations shown in the previous sections. Note also that, as the reporting rate is increased, the increase in the average packet delay is observed regardless of the number of actor nodes and wireless channel model.

In Fig. 12 and 13, it is also interesting to note that when the number of actors is increased from 4 to 8, the network is started to experience congestion in lower reporting rates compared to 4 actor scenarios. This is because when the number of actors is high, the exchange of several routing packets between sensors and multiple actors overloads the network unnecessarily, which decreases the network performance in terms of reliability and end-to-end latency. Hence, realizing the full potential of multiple actors in the deployment field requires careful network engineering including adaptive and lightweight data forwarding protocols.

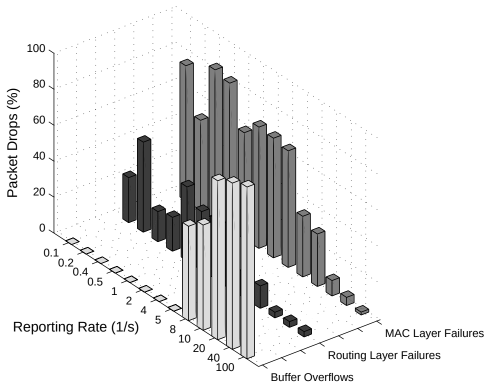

Fig. 14. **Distribution of packet drops due to buffer overflows, routing layer failures and MAC layer failures for different values of reporting rate.**

3.7 Reasons for Packet Drops

In this section, we investigate the distribution of packet drops for different reporting rates. As shown in Fig. 14, the distribution of packet drops depends on the reporting rate. As explained in Section 3.2, 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 actor 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 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.

3.8 Energy Efficiency

In WSN, energy efficiency is crucial due to constrained energy resources of the sensors. The developed protocols should consider the energy efficiency in the network while accomplishing their application-specific objectives. Hence, the

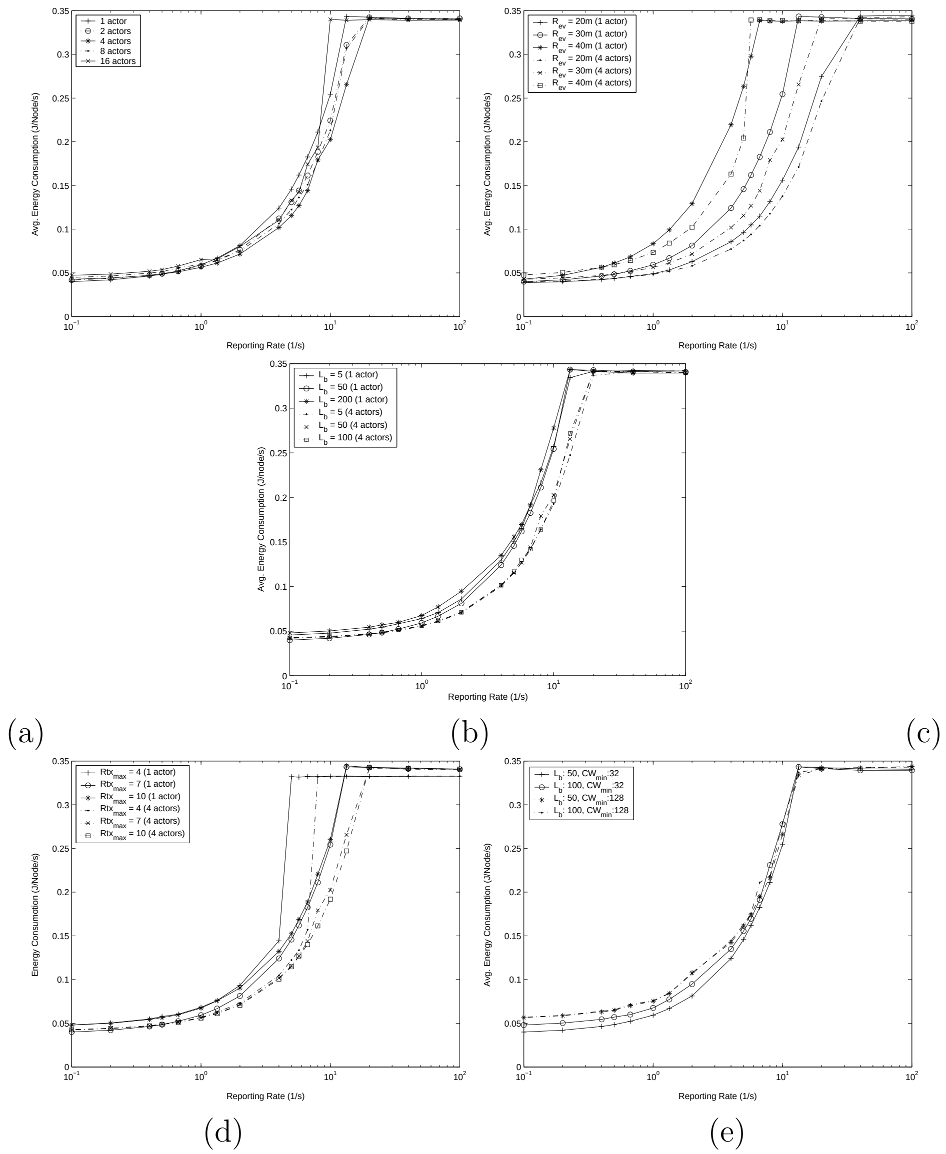

Fig. 15. **Average energy consumption per node for different (a) number of actors, (b) event radius, (c) buffer size, (d) retransmission limit, and (e) initial contention window.**

tradeoffs in energy consumption due to interactions among sensors is highly important to be investigated. In this section, we provide insightful results for the effects of different network parameters, such as number of actors, event radius, buffer size, MAC layer retransmission limit and contention window size on average energy consumption per sensor node.

The results of our simulations for different number of actors, event radius, buffer sizes, Rtx_{max} values, and initial contention window size CW_{min} are shown in Fig. 15 (a)-(e), respectively. In these figures, the average energy consumption per node per second in the WSAN is shown. As seen in these figures, an initial increase is observed as the reporting rate is increased. Moreover, a

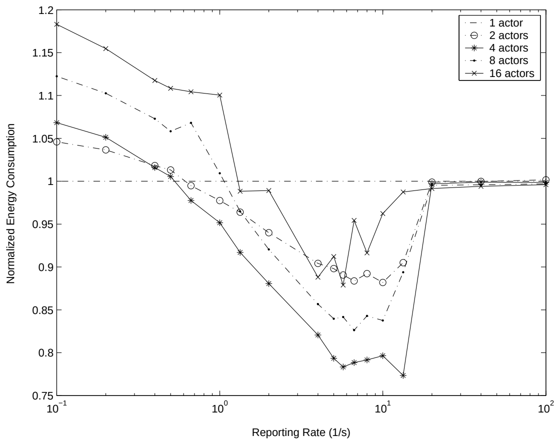

Fig. 16. Average energy consumption normalized to the energy consumption of a single actor scenario.

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 constant leading to constant energy consumption. However, note from our earlier discussions 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.

We first investigate the effect of actors on the energy consumption. As shown in Fig. 15 (a), the energy consumption for different number of actors is similar. However, there are still differences for each number of actors. In order to clearly illustrate the effect of number of actors, in Fig. 16, we plot the energy consumption normalized to the case of a single actors. This figure clearly shows the advantage of WSANs on WSNs, since the case with a single actor can be regarded as a WSN. As can be observed from Fig. 16, increasing the number of actors has positive impact on energy consumption above a certain reporting rate. The significance of impact the reporting rate at which energy savings start depend on the number of actors. Consistent with our earlier observations, 4 actors result in lowest energy consumption when compared to other cases. Moreover, 4 actors start to be more efficient than the single actor case at lower reporting rates. Consequently, decrease of 80% in the overall energy consumption is possible. Moreover, note that this saving is possible at lower reporting rates, where congestion is not observed. Another interesting result is that 2 actors result in lower energy consumption than 16 actors. This clearly shows that using many actors in a WSAN is not energy efficient. Rather an optimal number of actors has to be found considering the dynamics of the WSAN.

In Fig. 15(b), 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 actor. As shown in Fig. 15(b), 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. Moreover, a higher number of actors conserve energy as observed from the dotted lines in Fig. 15(b).

An interesting result obtained from Fig. 15(c) and (d) 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 3.3 and Section 3.4, these parameters have significant impact on network performance metrics. Hence, it is clear that buffer length and retransmission limit can be adjusted in WSAN protocols according to the application specific requirements without hampering the energy consumption of the nodes. On the other hand, Fig. 15(e) reveals that, increasing initial contention window size CW_{min} increases average consumed energy especially in the non-congested region. However, as discussed in Section 3.5, 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 number of actor nodes, buffer size, retransmission limit or contention window size can lead to efficient protocols in terms of event reliability, end-to-end latency, or energy consumption in WSANs. Therefore, the parameters of the developed protocols 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 for WSANs. The results of these experiments reveal interesting tradeoffs and interactions between different network parameters. The findings of our investigations can be summarized as follows:

- *Small buffer size is more efficient:* In the case of applications where event reliability can be afforded to be low, i.e., $ER_{ev} \simeq 90\%$, 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-actor 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 WSAN protocols according to the application specific requirements without hampering the energy consumption of the nodes.
- *Higher resolution vs. higher congestion:* In WSANs, 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.

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

Acknowledgments

The authors would like to thank Prof. Ian F. Akyildiz for his valuable comments that improved the quality of this paper. This material is based upon work supported by the National Science Foundation under Grant No. 0428329.

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.

[3] I. F. Akyildiz and I. H. Kasimoglu, "Wireless Sensor and Actor Networks: Research Challenges," *Ad Hoc Networks Journal (Elsevier),* vol. 2, no. 4, pp. 351-367, October 2004.

[4] I. F. Akyildiz, M. C. Vuran, and O. B. Akan, "A Cross-Layer Protocol for Wireless Sensor Networks," in *Proc. of CISS 2006*, Princeton, NJ, March 2006.

[5] I. F. Akyildiz, M. C. Vuran, O. B. Akan, and W. Su, "Wireless Sensor Networks: A Survey REVISITED," *to appear in Computer Networks Journal (Elsevier)*, 2007.

[6] V.C. Gungor, O.B. Akan, I.F. Akyildiz, "A Real-Time and Reliable Transport Protocol for Wireless Sensor and Actor Networks," *to appear in IEEE/ACM Transactions on Networking*, 2007.

[7] V.C. Gungor and O.B. Akan, "DST: Delay Sensitive Transport in Wireless Sensor Networks," in *Proc. of IEEE ISCN 2006*, Istanbul, Turkey, June 2006.

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

[9] IEEE 802.11 standard, "Wireless LAN medium access control (MAC) and physical layer (phy) specifications," 2001.

[10] Network Simulator, ns-2, *http://www.isi.edu/nsnam/ns/*.

[11] H. Nikookar and H. Hashemi, "Statistical Modeling of Signal Amplitude Fading Of Indoor Radio Propagation Channels," in *Proc. of International Conference on Universal Personal Communications*, vol.1,pp. 84-88, 1993.

[12] T. S. Rappapport, "Wireless Communications: Principles and Practice," Prentice Hall, 2002.

[13] 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.

[14] 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.

[15] 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.

[16] M. C. Vuran, V. C. Gungor, O. B. Akan, "On the Interdependence of Congestion and Contention in Wireless Sensor Networks," in *Proc. ICST SenMetrics 2005,* San Diego, CA, July 2005.

[17] M. Zuniga and B. Krishnamachari, "Analyzing the Transitional Region in Low Power Wireless Links," in *Proc. of IEEE SECON*, Santa Clara, CA, 2004.