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On the cross-layer interactions between congestion and contention in wireless sensor and actor networks

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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.

Keywords: Wireless sensor and actor networks; Congestion detection and control; Network contention; Cross-layer design

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 [2]. 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.

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

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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 [3,4]. 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.
- *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 [5]. 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 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.
- *Reporting Rate:* Mainly, WSAN applications can be classified into two classes, i.e., event-driven and periodic [2]. 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 [2]) 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 [2]) 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 [6,10]. 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 [2,9].

Majority of the congestion control algorithms proposed for sensor networks [1,6,10] 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 [10], channel load information from the MAC layer is incorporated into congestion detection and control mechanisms. In a converse approach, the authors in [11] transmission control scheme for use at the MAC layer in WSN is proposed. In [1], congestion detection is performed through buffer occupancy measurements. Furthermore, [6] 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 [6] that MAC layer support is beneficial in congestion detection and control algorithms.

In [12], 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 [12] 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 and number of sources, 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 retransmissions, and physical layer parameters on various network performance metrics are investigated in Sections 3.1–3.5, respectively. Moreover, the effects on energy efficiency is explored in Section 3.6. 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* [7]. The simulations are performed using this environment in a $100 \times 100\ \text{m}^2$ sensor field. Hundred sensors with radio ranges of 40 m are randomly deployed in this field. Moreover, 16 actors are placed evenly on a circle of radius 50 m. 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. 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 informa-

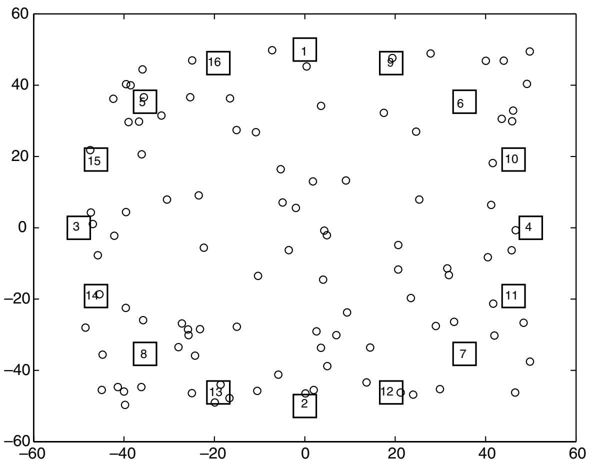

Fig. 1. Sample topology used in the simulations. The circles represent the sensors while the squares represent the actors.

tion 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.

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. We define the reliability as the percentage of total sent packets that are received at the actor nodes.

MAC Layer Errors: 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. The factors influencing this phenomenon are investigated through the percentage of the total sent packets lost due to buffer overflow.

End-to-end Latency: 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 50 m.

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 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

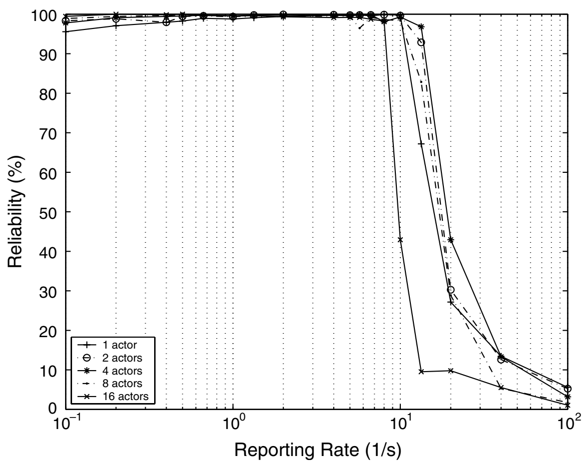

Fig. 2. Reliability versus reporting rate for different number of actors.

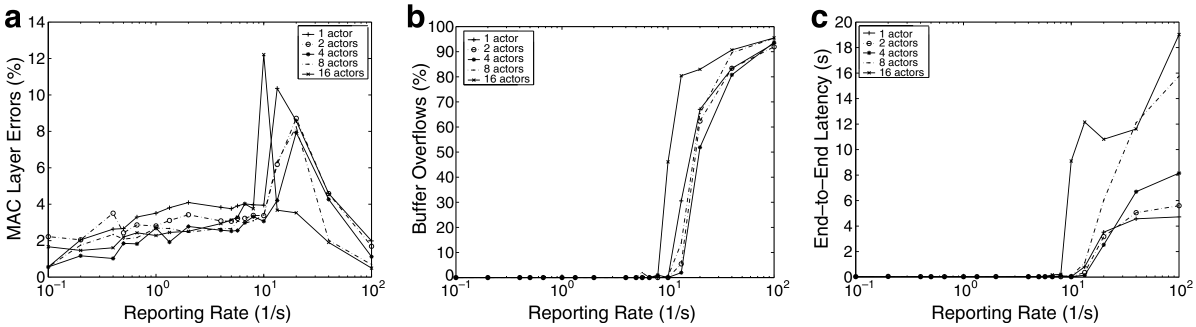

Fig. 3. (a) MAC layer errors, (b) buffer overflows, and (c) end-to-end latency versus reporting rate for different number of actors.

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 8 s^{-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 13 s^{-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 $r = 13\ s^{-1}$.

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 percentage of MAC layer errors are shown in Fig. 3(a).

This figure clearly reveals the effect of increased network load on the local channel contention. As shown in Fig. 3(a), the number of MAC layer errors 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(a). 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

[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.

are mostly resulting from buffer overflows in the network as shown in Fig. 3(b). It is also important to note that as the tradeoff caused by number of actors is still evident here. Sixteen 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(b). 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(b). When Fig. 3(a) and (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 scenario.

In Fig. 3(c) we show the average end-to-end latency of the event packets from sensor field to the actors. As seen in Fig. 3(c), the average end-to-end packet latency is low in the non-congested region. Beyond $r_{\mathrm{th}}^{\mathrm{low}}$, 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., 20 m, 30 m, and 40 m. 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 $r_{\mathrm{th}}^{\mathrm{low}}$ values. The reasons for this shift is two-fold. First reason is the increased 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

[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.

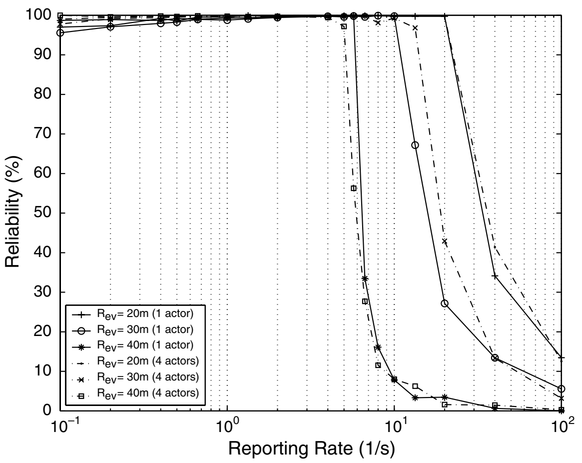

Fig. 4. Reliability versus reporting rate for different values of event radius.

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(b), we present the percentage of MAC layer errors. 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 Fig. 5(a). 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(b). 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(c) 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 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

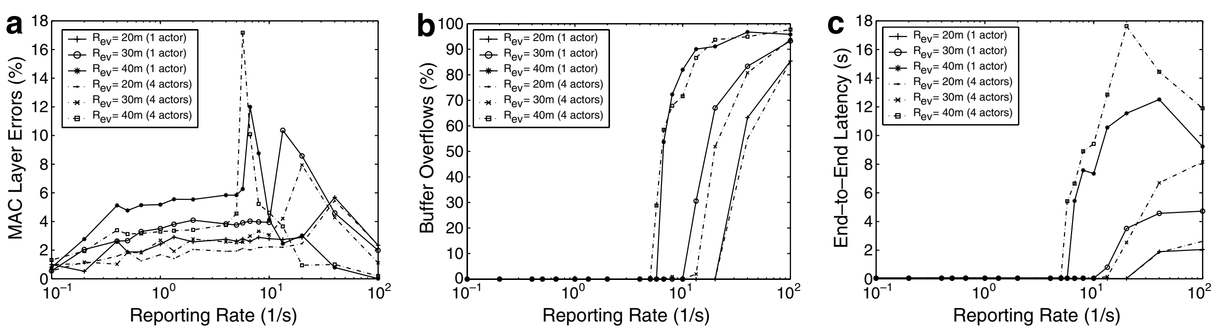

Fig. 5. (a) MAC layer errors, (b) buffer overflows, and (c) end-to-end latency versus reporting rate for different values of event radius, R_{ev}.

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.

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.

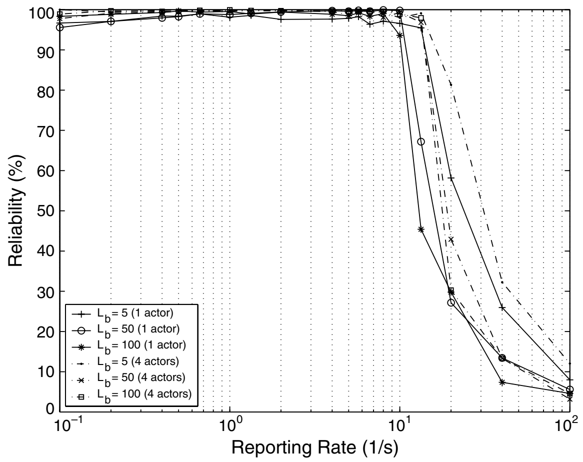

Fig. 6. Reliability versus reporting rate for different values of buffer length.

Increasing buffer size in WSAN has a negative effect on the local contention level as shown in Fig. 7(a). 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(a), 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(c), 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

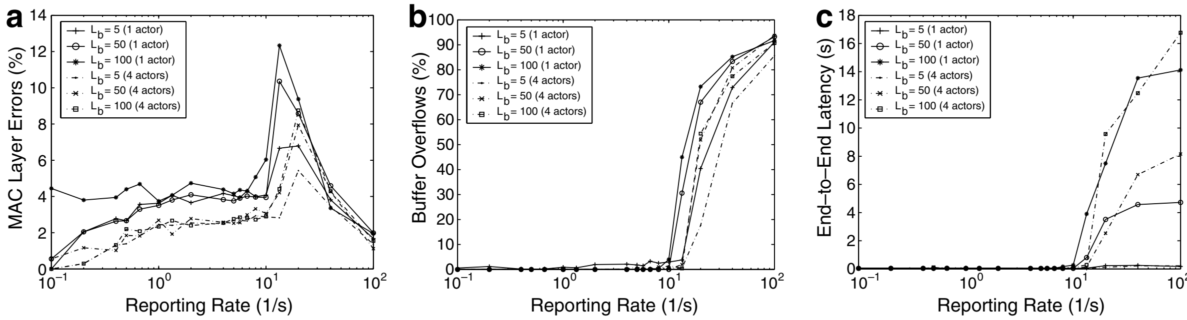

Fig. 7. (a) MAC layer errors, (b) buffer overflows, and (c) end-to-end latency versus reporting rate for different values of buffer length.

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., $ER_{\mathrm{ev}} \simeq 90\%$, 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 $r_{\mathrm{th}}^{\mathrm{high}}$. For lower values of $Rtx_{\max}$, the event reliability begins to decrease at lower $r_{\mathrm{th}}^{\mathrm{low}}$. 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 $r_{\mathrm{th}}^{\mathrm{low}}$ 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.

One of the tradeoffs in supporting higher reliability by adjusting the retransmission limit, $Rtx_{\max}$ is shown in Fig. 8(b), 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 mech-

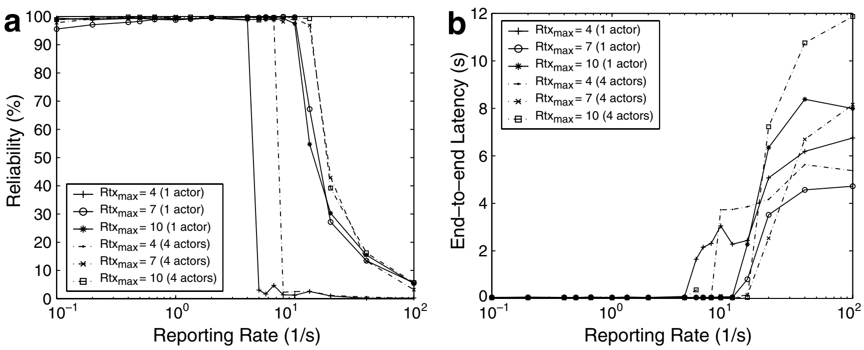

Fig. 8. (a) Reliability, and (b) end-to-end latency versus reporting rate for different values of retransmission limit, $Rtx_{\max}$.

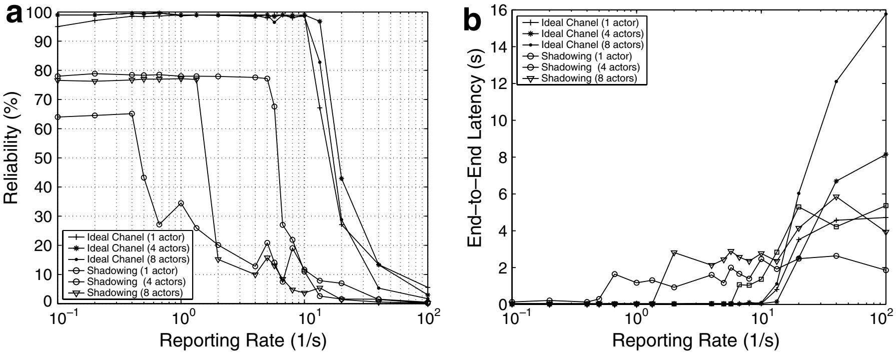

Fig. 9. Measurements with wireless realistic channel: (a) reliability versus reporting rate, (b) end-to-end latency versus reporting rate.

anism 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.

3.5. Wireless channel effects

When a radio signal propagates through the wireless environment, it is affected by reflection, diffraction and scattering [9]. 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 [9]. 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 wireless environments with obstructions [8,13]. In this model, the signal to noise ratio $\gamma(d)$ at a distance d from the transmitter is given by:

$$\gamma(d)_{\mathrm{dB}} = P_{\mathrm{t}} - PL(d_0) - 10\eta\log_{10}\left(\frac{d}{d_0}\right) - X_\sigma - P_{\mathrm{n}}, \tag{1}$$

where P_{t} is the transmit power in dB m, $PL(d_0)$ 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 dB m. In practice, the values of path loss exponent (η) and the standard deviation (σ) are computed from experimentally measured data. For example, η is 2–3 for indoor environments with obstructions and σ ranges from 2 to 5 based on different environment characteristics [9,13].[4]

In Fig. 9(a), we have shown the impact of the number of actors and the realistic wireless channel on the overall event reliability. As shown in Fig. 9(a), 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. 9(a), 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 $r_{\mathrm{th}}^{\mathrm{low}}$.

In Fig. 9(b), we also observe the average end-to-end latency of the event packets when the realistic

[4] In our simulation experiments, we have used $\eta = 3.0$ and $\sigma = 3.8$, which are typical values found by experiments in [13] for indoor environments.

wireless channel is modelled. As shown in Fig. 9(b), 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. 9(a) and (b), 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.

3.6. 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 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 on average energy consumption per sensor node.

The results of our simulations for different number of actors, event radius are shown in Fig. 10(a) and (b), 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 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. 10(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. 10(c), 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. 10(c), increasing the number of actors has positive impact on energy consumption above a certain reporting rate. The significance of

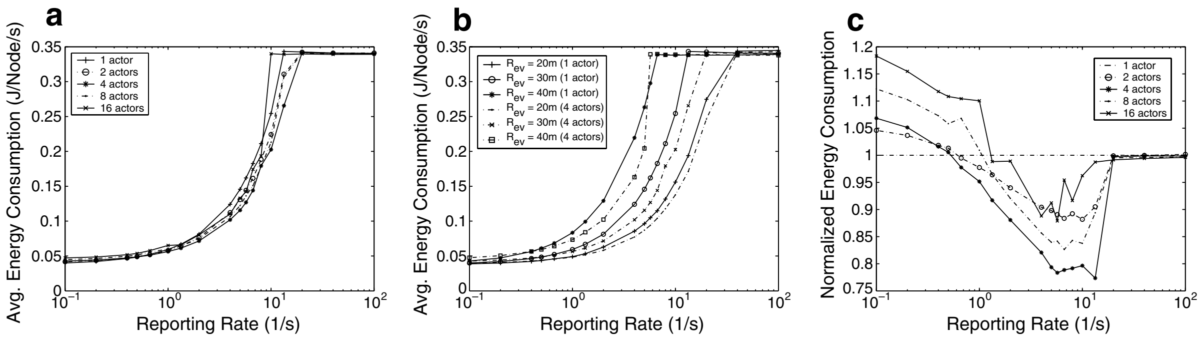

Fig. 10. (a) Average energy consumption per node for different number of actors, (b) average energy consumption per node for different event radius, and (c) average energy consumption normalized to the energy consumption of a single actor scenario.

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. 10(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. 10(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. 10(b).

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 num-

ber 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 reveal that local interactions between sensors and actors directly affect the overall network performance. The interdependency between network parameters calls for adaptive cross-layer mechanisms for efficient data delivery in wireless sensor and actor networks.

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