Using Wireless Advantage for Congestion Control in Wireless Sensor Networks

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***Abstract*— In this paper we present a proof of concept that wireless advantage can be used for congestion control in wireless sensor networks. We show through simulations that for delay–tolerant, loss–intolerant data wireless advantage can be used to ensure 100% data delivery for different source data generation rates and queue sizes at intermediary nodes. We analyze the queue dynamics in the wireless sensor network using fluid models and exponential back-off based service rate models and show that they match the simulation results closely.**

I. Introduction

Wireless sensor networks (WSN) has been drawing increasing interest from the research community in recent times due to the numerous applications in which WSN can be used. One of the many such applications is environment monitoring through a variety of devices with different energy constraints. This application requires the sensor devices to report any abrupt events to one or more sinks apart from performing their main operation of environment sensing. The abrupt events generate impulses of large amounts of data which might lead to congestion in the WSN. Even though the impulses may last for a few time units, the data traffic generated during the events is very important and loss–intolerant. Depending on the application, this data can either be delay tolerant or delay intolerant. In this paper, we study the specific case of delay–tolerant, loss–intolerant data (In the rest of this paper "data" refers to delay–tolerant, loss–intolerant data).

In order to mitigate the congestion resulting from transporting large amounts of data from sources to sinks a distributed, energy efficient congestion control scheme is required. The traditional method of congestion control is reducing the data source rate through implicit (e.g. TCP in wired networks) or explicit signalling schemes. The implicit schemes assume that the network is congested when packets are dropped, and this requires an end-to-end acknowledgement (ARQ) mechanism. In explicit schemes the data source reduces the rate when intermediary nodes inform the source of congestion in the network. Most of the congestion control mechanisms employ a congestion avoidance scheme also in order to maintain good throughput.

In this paper we explore a new approach at congestion control which makes use of wireless advantage to arrest packet drop due to congestion and ensure that all the data reaches the sink without loss. Wireless advantage (or broadcast advantage) is the property of wireless networks in which a wireless node can listen to all the communication of its neighbors owing to the broadcast nature of the wireless channel. Simulation results show that wireless advantage can be effectively used to ensure 100% packet delivery to the sink over different source data rates and queue sizes at intermediary nodes. Simulation results also show that the delay of data delivery increases when wireless advantage is used, as expected. We develop analytical models that govern the queue dynamics at the source nodes as well as the intermediary nodes and compare them with the simulation results.

The rest of the paper is organized as follows: Section II discusses the related work in congestion control in WSN. In section III a detailed description of our new approach is provided and section IV presents the evaluation of our approach through simulations. Section V analyzes the queue dynamics of the wireless network and compares the analytical model with simulation results. We conclude in section VI and discuss the future direction of our work in section VII.

II. Related Work

This section describes related work on congestion control. C.Y.Wan et al in [3] propose a congestion control scheme called CODA which mainly consists of three parts, congestion detection, open-loop hop-by-hop back-pressure and closed loop multi source regulation. The authors use a combination of past and present channel loading conditions and current buffer occupancy in conjunction with a low cost channel listening mechanism for congestion detection in the sensor network. When congestion is detected nodes broadcast back-pressure messages to the source and the source reduces its transmission rate accordingly. In the case of persistent congestion the source enters a closed congestion control based on ACK messages from the sink.

In a closely related work the authors in [1] present three congestion control techniques operating at different layers of the protocol stack and show that the performance when all the three techniques are used in conjunction is far better than when they are used individually. Not unlike [3], the authors use hop-by-hop flow control to signal local congestion using back-pressure messages and congestion bits to reduce packet

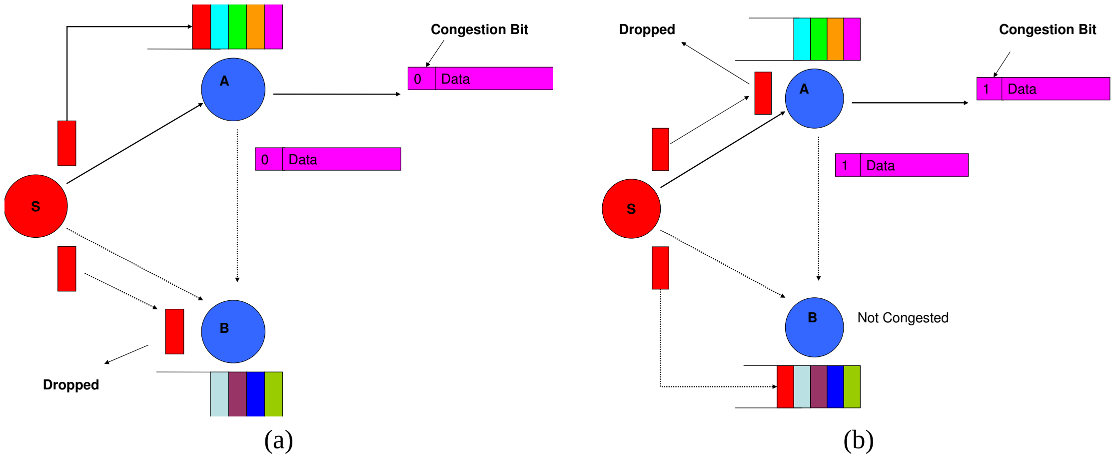


Fig. 1. (a) If A is not congested (congestion bit is reset), B drops the packet. (b) If A is congested (congestion bit is set), B stores the packet if it is not congested and A drops the packet.

loss rates. They also use a source rate limiting scheme which is fair to both far away and near by sources. They propose a prioritized MAC layer technique to avoid packet drops at congested nodes.

Next we describe our approach at mitigating congestion in wireless networks. We borrow from the above two efforts for detecting congestion and informing the neighboring nodes of the presence of congestion.

III. A New Approach

In this section we present our technique of ensuring 100% data delivery by controlling congestion using *wireless advantage* in wireless sensor networks. The advantage of wireless connections is that all nodes in the radio range of the source receive the packet even though it may be destined to only one of the nodes. This advantage can be potentially used for congestion control.

There are potentially many ways to detect when the network is approaching congestion. One of them is when the buffers in intermediary nodes exceed a certain threshold and another method could be when one or two nodes are completely out of buffer space. When congestion is imminent, wireless advantage is used to reduce the load on the congested node by allowing neighboring nodes to "pretend" to be the forwarding node. We borrow the idea of "congestion bit" from previous work [3] to indicate congestion to the neighbors of the congested node. Figure 1 illustrates the whole technique through a simple example of three nodes.

When source S sends out a packet to an intermediary node A in the route to the sink, other nodes (say, B, if there is only one) in the radio range of S also receive and store the packet intended to A. If node A is not congested, the congestion control bit in the packet (need not be the present packet from the source) forwarded by A to the next node in the route to the sink is reset. Since B will be able to overhear this packet from A, it drops the original packet from source knowing that A is not congested. If node A is congested (i.e., the network is approaching congestion) the congestion bit is set and A drops the present packet from its queue and B, which is not congested, will forward the present packet to the sink.

In this mechanism, adjacent nodes share the load of packet forwarding and thus avoid any potential bottle necks and could increase the network throughput substantially. Inherently, all nodes, except the forwarding node, hold the packet they receive at-most for one time slot. In the next two sections we provide thorough evaluation and analysis of this technique for congestion control.

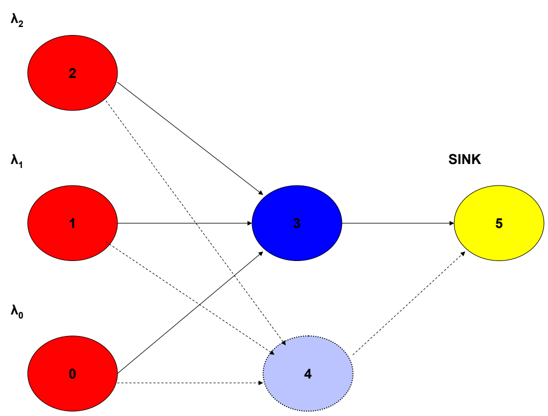


Fig. 2. A simple example to illustrate congestion control using wireless advantage.

IV. Evaluation

We evaluate our congestion control technique through simulations using GlomoSim [7]. As described previously we are interested in studying congestion resulting from impulses of data for a short duration of time. The evaluation is done using a simple example described next.

A. A Simple Example

We consider a simple example of five nodes as shown in figure 2 to illustrate the concept of using wireless advantage for congestion control. The data sources $\{0, 1, 2\}$ generate data

Parameter	Value
Source	CBR traffic over UDP
Source ON Time	$0 - 1800$ seconds
Simulation Time	150 minutes
Link Bandwidth	12 kbps
MAC Protocol	802.11 RTS/CTS
Application Packet Size	36 Bytes
Queue Size	14300 packtes

TABLE I

SIMULATION PARAMETERS.

at rates $\{\lambda_0, \lambda_1, \lambda_2\}$ respectively. A static routing table routes the packets from the three sources through intermediate node 3 to sink 5. When node 3 is congested and as long as it is congested, node 4 forwards the packets instead of node 3.

Node 4 in the promiscuous mode keeps track of the congestion at node 3 through the congestion bit. When node 3 is not congested, node 4 drops all the packets it receives from the sources. When node 4 detects congestion at node 3, it starts storing packets from the three sources, assuming that node 4 is in the radio range of all the three sources.

Table I lists the various simulation parameters. For source data generation rates of $\{\lambda_0 = 10, \lambda_1 = 4, \lambda_2 = 4\}$ packets/sec respectively for sources $\{0, 1, 2\}$, the queue size at node 3 reaches a maximum of 14202 packets. In order to avoid packets drops the maximum queue size for the nodes was chosen to be 14300 packets. Figure 3 shows the queue behavior at the source nodes and the intermediate node 3 as a function of the simulation time when there is no congestion (i.e., node 4 is not used).

The queue size of source 0 increases at a higher rate (greater slope in figure 3(a)) than the queue sizes of sources 1 and 2 because its arrival rate is higher and all the three sources have the same service rates. Since the sources are on for 1800 secs the source queue sizes increase till that time and start decreasing after that. The queues of sources 1 and 2 are emptied faster than the queue of source 0 because their queues have fewer packets than the queue of source 0. When the queues of sources 1 and 2 are empty the service rate of sources 0 and the intermediate node 3 increases because there are fewer nodes accessing the channel. From figure 3(d) it can be seen that the queue size of node 3 increases till all the source nodes have packets to transmit, which is till the last packet transmission of source nodes 1 and 2. After that, only source node 0 transmits packets and node 3 forwards them to the sink. Since the arrival and departure rates are equal at this time the queue size remains constant until all the packets in the queue of source node 0 are transmitted. When source node 0 has finished sending its packets, the service rate at node 3 increases further as there are only two nodes (node 3 and the sink) in the network and this is shown in the slope of the plot after 5000 secs in figure 3(d).

B. Does Wireless Advantage Work?

In order to evaluate if wireless advantage works for the simple scenario considered above, we consider two cases:

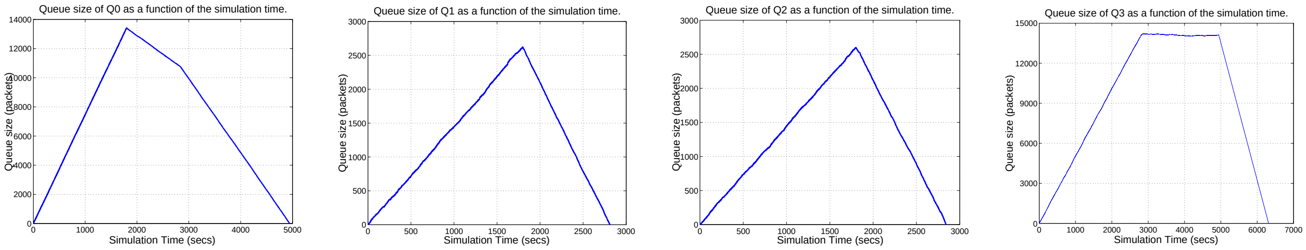
1) Increased Source Data Rate, Unchanged Queue Size: In this case the source data rate of source 1 is increased and the data rates of sources 0 and 2 are maintained at the same level as the original case (as described above). The new data rates are $\{\lambda_0 = 10, \lambda_1 = 10, \lambda_2 = 4\}$. The queue size at the nodes is maintained unchanged from the original case and as a result more traffic is generated than the queue at the intermediate node 3 can handle. This leads to congestion (queue overflow) at node 3 and the congestion bit is set. Node 4, in the promiscuous mode, senses the congestion at node 3 and starts forwarding packets as long as node 3 is congested. When congestion at node 3 reduces node 4 stops admitting extra packets leaving the packet admission to node 3. Figure 4 plots the queue sizes of source nodes 0, 1 and 2 and figure 5 plots the queue sizes of forwarding nodes 3 and 4 as a function of the simulation time.

From figure 4(a) it can be seen that Q_0 follows the same graph for the original case, increased-rate-non-promiscuous and increased-rate-promiscuous modes until source node 2 is emptied (figure 4(c)). After this time, for the increased-rate-non-promiscuous and increased-rate-promiscuous modes, the queue discharge rate is slower (smaller slope) than the original case because during this time three nodes are active in the original case whereas for the increased-rate-non-promiscuous and increased-rate-promiscuous modes four and five nodes are active respectively, thus reducing the service rates. These dynamics are evident through the slopes in figure 4(a). Figure 4(b) clearly shows the same dynamics where the slope of the plot is higher for increased-rate-non-promiscuous than for increased-rate-promiscuous modes owing to higher service rate.

Figure 5(a) plots the queue size of forwarding node 3 and it shows that the zero queue growth is longer for increased-rate-non-promiscuous mode than for that of the original case and it is even longer for increased-rate-promiscuous mode. But the queue discharge rates (slopes) are the same for the three cases. These dynamics are again a direct consequence of the different service rates for different modes. Figure 5(b) shows that wireless advantage if used intermittently by the network and not continuously for this case.

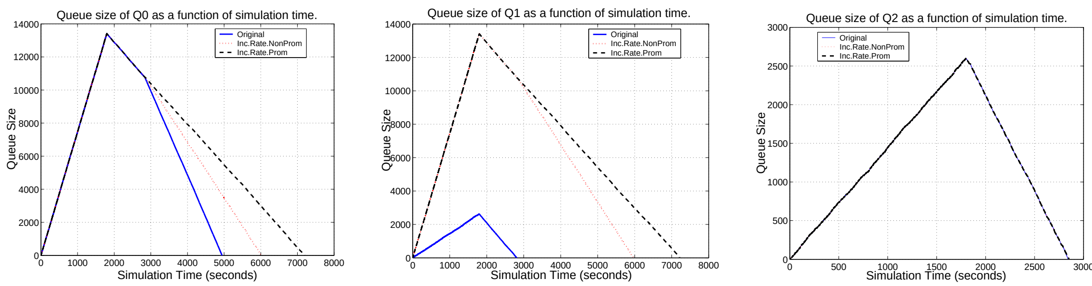
Table II lists the packet delivery rate and average end-to-end delay for the cases when wireless advantage was used and when it was not used (or, when node 4 was in promiscuous mode and not in promiscuous mode respectively). As expected, using wireless advantage ensures 100% packet delivery, even though, the average end-to-end delay of the network increases. The reason for this is that, when a new node is introduced into the network, the service rate of individual nodes decreases owing to the broadcast nature of the wireless channel and thus the queueing delay of all packets during congestion increases.

2) Reduced Queue Size, Unchanged Source Data Rate: In this case the source data rates are unchanged and the queue size of node 3 is reduced to 7000 packets. This leads to queue overflow at node 3 and node 4 starts accepting and forwarding packets to the sink. Figure 6 plots the queue sizes of source nodes 0, 1 and 2 and figure 7 plots the queue sizes



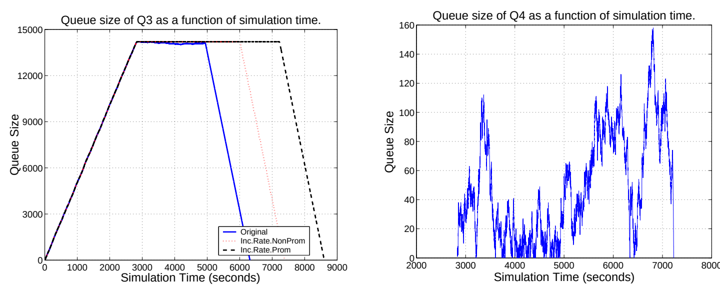
(a) (b) (c) (d)

Fig. 3. Queue behavior as a function of the simulation time for source data generation rates of $\{\lambda_0 = 10, \lambda_1 = 4, \lambda_2 = 4\}$.



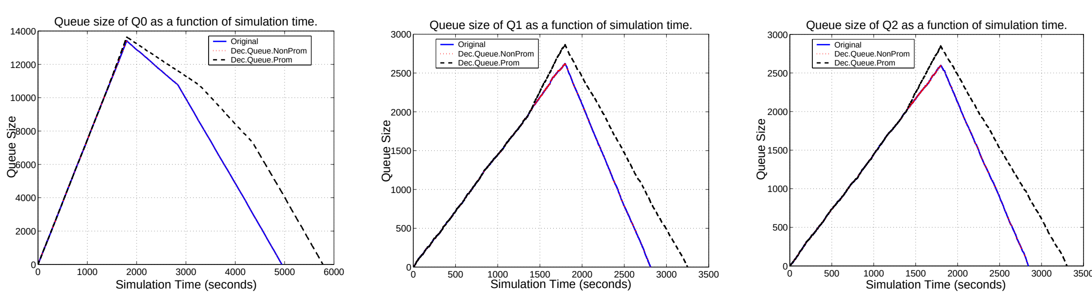
(a) (b) (c)

Fig. 4. Queue sizes of source nodes 0 (a) 1 (b) and 2 (c) as a function of the simulation time for increased source data rates $\{\lambda_0 = 10, \lambda_1 = 10, \lambda_2 = 4\}$ and constant queue sizes. The figures plot the *original* statistics (when the source data rate is not increased), *increased rate non promiscuous mode* statistics (when the wireless advantage is not used) and *increased rate promiscuous mode* statistics (when the wireless advantage is used).



(a) (b)

Fig. 5. Queue sizes of forwarding nodes 3 (a) and 4 (b) as a function of the simulation time for increased source data rates $\{\lambda_0 = 10, \lambda_1 = 10, \lambda_2 = 4\}$ and constant queue sizes. The figures plot the *original* statistics (when the source data rate is not increased), *increased rate non promiscuous mode* statistics (when the wireless advantage is not used) and *increased rate promiscuous mode* statistics (when the wireless advantage is used).

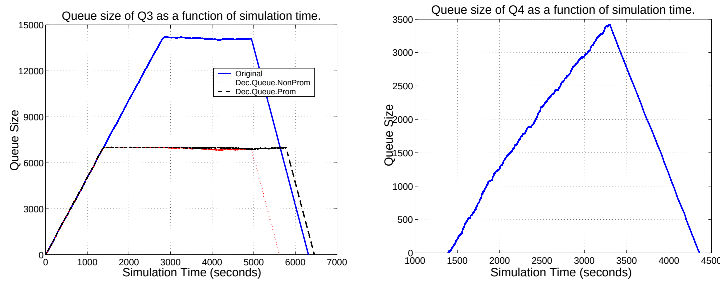


(a) (b) (c)

Fig. 6. Queue sizes of source nodes 0 (a) 1 (b) and 2 (c) as a function of the simulation time for reduced queue size at node 3 to 7000 packets from 14300 packets and when source data rates remain unchanged. The figures plot the *original* statistics (when the queue size is not reduced), *decreased queue size non promiscuous mode* statistics (when the wireless advantage is not used) and *decreased queue size promiscuous mode* statistics (when the wireless advantage is used).

of forwarding nodes 3 and 4 as a function of the simulation time.

Figure 6(a) shows that Q_0 follows the same graph for the original case and the decreased-queue-size-non-promiscuous



(a) (b)

Fig. 7. Queue sizes of forwarding nodes 3 (a) and 4 (b) as a function of the simulation time for reduced queue size at node 3 to 7000 packets from 14300 packets and when source data rates remain unchanged. The figures plot the *original* statistics (when the queue size is not reduced), *decreased queue size non promiscuous mode* statistics (when the wireless advantage is not used) and *decreased queue size promiscuous mode* statistics (when the wireless advantage is used).

Parameter	Without WA	With WA
Packet Delivery to Sink	75.3%	100%
Average End to End Delay	66 mins	80 mins

TABLE II

PACKET DELIVERY AND AVERAGE END-TO-END DELAY METRICS FOR THE CASE OF INCREASED SOURCE DATA RATE AND UNCHANGED QUEUE SIZES, WITH AND WITHOUT WIRELESS ADVANTAGE.

Parameter	Without WA	With WA
Packet Delivery to Sink	77.4%	100%
Average End to End Delay	45 mins	53 mins

TABLE III

PACKET DELIVERY AND AVERAGE END-TO-END DELAY METRICS FOR THE CASE OF REDUCED QUEUE SIZE AND UNCHANGED SOURCE DATA RATES, WITH AND WITHOUT WIRELESS ADVANTAGE.

mode because only the queue size of node 3 is reduced even as the queue size of node 0 is kept the same. Similarly, for $Q1$ and $Q2$ the plots are the same for the original case and the decreased-queue-size-non-promiscuous mode. For the decreased-queue-size-promiscuous mode, because of the active presence of node 4 during the congestion period (which is evident from figure 7(b)), the service rate (the slope) is lower. This is evident from the slopes of the decreased-queue-size-promiscuous mode plots for all the three source nodes 0 (figure 6 (a)) , 1 (figure 6(b)) and 2 (figure 6(c)). For source node 0 once the congestion period has expired only three nodes are active (instead of four during the congestion period after nodes 1 and 2 are emptied) and again there is a change in the slope (increase service rate) which can be clearly seen in figure 6(a). The queue dynamics of node 3 closely follow the above analysis as shown in figure 7(a).

Table III lists the packet delivery rate and average end-to-end delay for the cases when wireless advantage was used and when it was not used. As in the previous case, our technique using wireless advantage ensures 100% packet delivery, albeit with increased end-to-end delay.

V. ANALYSIS

In this section we provide analytical reasoning for the queue dynamics using some simple fluid models. The service rate of the nodes is dependent on the number of nodes and the exponential back-off mechanism employed by 802.11 MAC for collision avoidance. Below, we provide a brief description of the procedure for calculating the average service rate for each wireless node in the network. This analysis has been described in detail in [4], [6] and we use the results from these papers without any change.

A. Service Rate

The average service time at a node in a wireless network employing exponential back-off algorithm is given by the sum of the average back off time and the average time to successfully transmit a packet.

$$\overline{ST} = \overline{T}_B + t_s \tag{1}$$

When a node detects the medium as busy, it goes into the back off mode and its back-off timer decrements based on the channel condition. If the medium is sensed idle, the back-off timer is decrement, otherwise it is frozen until the medium is sensed idle again for more than DIFS time at which time, the back-off timer decrement resumes. At each packet transmission the back-off timer is uniformly chosen in the interval $(0, W-1)$ where W is the contention window size that takes an initial value of W_{min} and a maximum value of $W_{max}(= 2^m W_{min})$.

The average back off time ($\overline{T}_B$) is derived in [4] to be:

$$\overline{T}_B = \frac{\alpha(W_{min}\beta - 1)}{2q} + \frac{(1-q)}{q} t_c \tag{2}$$

Where,

$$\alpha = \sigma p_i + t_c p_c + t_s p_s \tag{3}$$

$$\beta = \frac{q - 2^m(1-q)^{m+1}}{1 - 2(1-q)} \tag{4}$$

$$q = 1 - p \tag{5}$$

where, p is the probability that a packet being transmitted in the medium experiences a collision, p_i is the probability of an idle time slot (σ), p_c is the probability of collision in a time slot, t_c is the collision time, p_s is the probability of successful transmission in a time slot and t_s is the time to successfully transmit a packet. Intuitively, the average time a packet spends in back-off is the average number of back-off stages it goes through (which is $\frac{1}{q}$) times the average time it spends in each back-off stage (which is $\alpha\frac{(W_{min}\beta-1)}{2}$) plus the average time spent on collision resolution (which is $(1-q)t_c$). $W_{min}\beta$ can be viewed as the "effective" window size. These values can be calculated using:

$$p = \frac{2W_{min}(n-1)}{(W_{min}+1)^2 + 2W_{min}(n-1)} \tag{6}$$

$$p_i = 1 - P_{tr} \tag{7}$$

$$p_c = P_{tr}(1 - P_{suc}) \tag{8}$$

$$p_s = P_{tr}P_{suc} \tag{9}$$

$$t_s = RTS + SIFS + \delta + CTS + SIFS + \delta + H + PAYLOAD + SIFS + \delta + ACK + DIFS + \delta \tag{10}$$

$$t_c = RTS + DIFS + \delta \tag{11}$$

where, P_{tr} is the probability that there is one transmission in a given time slot and P_{suc} is the probability that a transmission occurring in the medium is successful, which are given by:

$$P_{tr} = 1 - (1-\tau)^{n-1} \tag{12}$$

$$P_{suc} = \frac{(n-1)\tau(1-\tau)^{n-2}}{1-(1-\tau)^{n-1}} \tag{13}$$

τ is the probability that a node transmits in a randomly chosen time slot and can be calculated using,

$$\tau = \frac{2W_{min}}{(W_{min}+1)^2}(1-p) \tag{14}$$

Table IV lists the values for all the above variables used in the simulations. Having calculated the average service time as described above, the average service rate (μ) is given by

$$\mu = \frac{1}{\overline{\overline{ST}}} \tag{15}$$

Figure 8 plots the average service rate as a function of the number of nodes in the wireless medium for the simulation parameters listed in tables I and IV. From this figure it can be seen that with increasing number of nodes in the network the service rate decreases.

Next we describe how the above analysis for average service rate can be used to explain the simulation results of figure 3 using simple fluid models.

Parameter	Value
Phy Layer Packet size	92 Bytes
RTS Packet Size	20 Bytes
CTS/ACK Packet Size	14 Bytes
SIFS	$10\mu secs$
DIFS	$50\mu secs$
Slot Size (σ)	$20\mu secs$
Propagation Delay (δ)	$1\mu sec$
Initial Contention Window Size (W_{min})	32
Maximum Contention Window Size (W_{max})	1024 ($m = 5$)

TABLE IV

PARAMETERS TO CALCULATE THE AVERAGE SERVICE RATE.

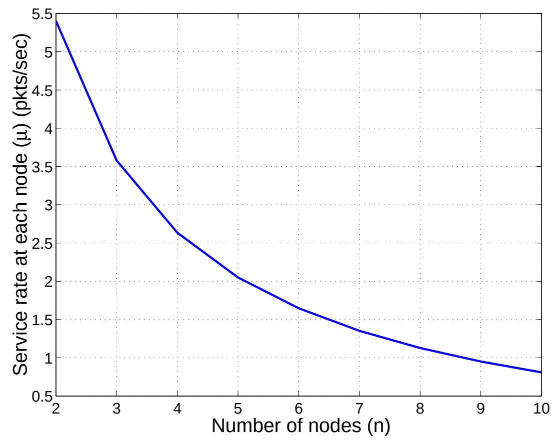


Fig. 8. Average service rate per wireless node as a function of the number of nodes in the wireless network.

B. Queue Dynamics

Fluid models can be used to determine how network variables vary with time. For the example and parameters described in section IV-A, the queue dynamics can expressed as follows:

For $0 \le t \le 1800\ sec$, $\{\lambda_0 = 10, \lambda_1 = 4, \lambda_2 = 4\}$, all the five nodes are active and the corresponding service rate is $\mu_1 = 2.1$ pkts/sec. Therefore, the differential equations describing the queue sizes can be written as:

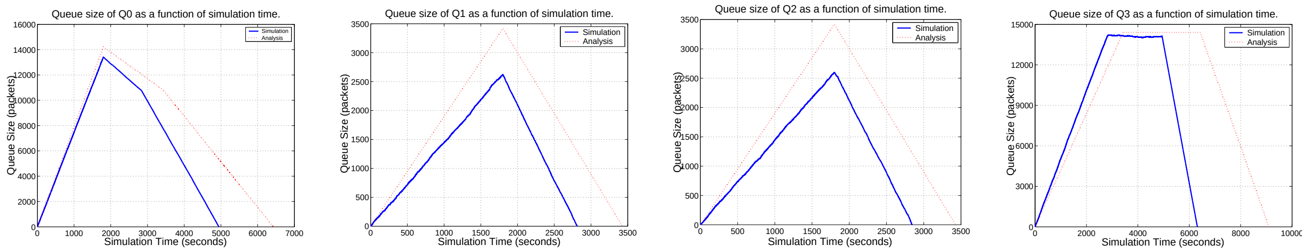
$$\frac{dQ_0}{dt} = \lambda_0 - \mu_1 = 7.9 \tag{16}$$

$$\frac{dQ_1}{dt} = \lambda_1 - \mu_1 = 1.9 \tag{17}$$

$$\frac{dQ_2}{dt} = \lambda_2 - \mu_1 = 1.9 \tag{18}$$

$$\frac{dQ_3}{dt} = 3\mu_1 - \mu_1 = 2\mu_1 = 4.2 \tag{19}$$

For $t > 1800\ sec$, the sources do not generate any more packets but they transmit queued up packets. As described previously, queues of sources 1 and 2 have fewer packets queued up than that of source 0. Therefore, all five nodes are active until the time queues of nodes 1 and 2 are emptied.



(a) (b) (c) (d)

Fig. 9. Comparison of queue dynamics as seen through simulations with analytical results.

$$\begin{aligned} At\ t &= 1800\,\text{sec}, Q_1 = Q_2 = 1.9 \times 1800 = 3420 \\ For\ t &> 1800\,\text{sec},\ \frac{dQ_1}{dt} = \frac{dQ_2}{dt} = -\mu_1 = -2.1 \\ \Rightarrow Q_1 = Q_2 = 0\ at\ t &= 1800 + \frac{3420}{2.1} = 3429\,\text{sec}\,. \end{aligned} \tag{20}$$

$$\begin{aligned} At\ t &= 1800\,\text{sec}, Q_0 = 7.9 \times 1800 = 14220 \\ For\ 1800\,\text{sec} < t &\leq 3429\,\text{sec},\ \frac{dQ_0}{dt} = -\mu_1 = -2.1 \\ \Rightarrow At\ t &= 3429\,\text{sec}, Q_0 = 14220 - 2.1 \times 1629 = 10800 \end{aligned} \tag{21}$$

$$\begin{aligned} For\ 0 \leq t \leq 3429\,\text{sec},\ \frac{dQ_3}{dt} &= 3\mu_1 - \mu_1 = 2\mu_1 = 4.2 \\ \Rightarrow At\ t = 3429\,\text{sec}, Q_3 &= 4.2 \times 3429 = 14401 \end{aligned} \tag{22}$$

For $t > 3429\,\text{sec}$, only the queue of source 0 has packets among all the three sources. Therefore, only three nodes (0, 3 and the sink) are active and the corresponding service rate is $\mu_2 = 3.6$ pkts/sec.

$$\begin{aligned} For\ t > 3429\,\text{sec},\ \frac{dQ_0}{dt} &= -\mu_2 = -3.6 \\ \Rightarrow Q_0 = 0\ at\ t = 3429 + \frac{10800}{3.6} &= 6429\,\text{sec} \end{aligned} \tag{23}$$

$$For\ 3429\,\text{sec} < t \leq 6429\,\text{sec},\ \frac{dQ_3}{dt} = \mu_2 - \mu_2 = 0 \tag{24}$$

For $t > 6429\,\text{sec}$, only node 3 and the sink are active. Therefore, the new service rate is $\mu_3 = 5.4$ pkts/sec.

$$\Rightarrow Q_3 = 0\ at\ t = 6429 + \frac{14401}{5.4} = 9096\,\text{sec} \tag{25}$$

Figure 9 plots the above analysis and compares it with the simulation results. As can be seen, the analysis matches the simulation results closely but not completely. One of the possible reasons for this could be that, in the analysis the nodes can retransmit infinitely. But in the simulations this is not true as the maximum of number of retransmissions is limited to seven. Similar fluid model based analysis can be provided for the other simulation results easily.

VI. Conclusion

In the paper a proof of concept has been provided using a simple example to show that wireless advantage can be used for congestion control in wireless sensor networks. Simulation results suggest that 100% packet delivery rate can be achieved, albeit with increased end-to-end delay, using wireless advantage when the data is delay-tolerant and loss-intolerant. We have also analyzed the queue dynamics using simple fluid models and exponential back-off based service rate models.

VII. Future Work

As part of the future work we would like to conduct simulations for more realistic scenarios with many wireless nodes. In the example described in this paper the forwarding node had only one forwarding neighbor. But in a more general scenario that is rarely the case. It is required to determine how many nodes and which neighboring nodes of the congested nodes will forward the packets instead. Also, intuition says that if a node is congested its neighbors might also be congested. It remains to be seen how this affects the performance of the congestion control mechanism using wireless advantage. In the future, we would also like to explore queuing models based analysis for queue dynamics.

Acknowledgements

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