On Improving the Reliability of Packet Delivery in Dense Wireless Sensor Networks

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***Abstract*—Wireless sensor networks (WSN) built using current Berkeley Mica motes exhibit low reliability for packet delivery. There is anecdotal evidence of poor packet delivery rates from several field trials of WSN deployment. All-to-one communication pattern is a dominant one in many such deployments. As we scale up the size of the network and the traffic density in this communication pattern, improving the reliability of packet delivery performance becomes very important.**

This study is aimed at two things. Firstly, it aims to understand the factors limiting reliable packet delivery for all-to-one communication pattern in dense wireless sensor networks. Secondly, it aims to suggest enhancements to well-known protocols that may help boost the performance to acceptable levels. We first postulate the potential reasons hampering packet delivery rates with current CSMA-based MAC layer used by the radios deployed in WSN. We then propose a set of enhancements that are aimed to mitigate the ill-effects of these factors. We pick three protocols, namely, Flooding, AODV, and Geographic routing as candidates for this study. Using TOSSIM, we perform a detailed study of these protocols and the proposed enhancements. This study serves several purposes. First, it helps us to quantify the detrimental effects of these factors. Second, it helps us to quantify the extent to which our proposed enhancements improves packet delivery performance. Concretely, we show that using Geographic routing in a WSN with 225 nodes spread over 150 feet x 150 feet, the proposed enhancements yield a 23-fold improvement in packet delivery performance over the baseline. Further, the enhancements result in fairness (measured by the number of messages received from each node at the destination). Lastly, we show that the overhead (in terms of retransmissions, acknowledgement messages, and control messages) is reasonable.

I. INTRODUCTION

Wireless sensor networks (WSN) built using Berkeley Mica motes have been hampered by unreliable packet delivery. Since the major role of sensor networks is sensing and delivering data to sink node, reliability is an important characteristic. Moreover, since data from as many of the sensing nodes as possible should be delivered to the destination, fairness becomes a substantial issue. Because packet loss gets worse through multi-hop routing paths in wireless sensor networks, nodes near the destination have higher packet delivery performance. A fundamental challenge is to understand the underlying limiting factors that prevent reliability and fairness. With a comprehensive understanding, each layer can exploit the lessons learned to achieve reliable packet delivery.

There is anecdotal evidence of poor packet delivery rates from several field trials of WSN deployment. Zhao *et al*. [15] show the prevalence of gray areas in which neighbor nodes receive less than half of the packets and significant asymmetry in a realistic environment. In their indoor experiments, half the links experienced more than 10% packet loss while 30% packet loss is experienced by a third of the links. There are many reasons for packet loss. The most significant ones include: 1) signal attenuation due to the distance between the nodes, 2) asymmetry in wireless communication links, 3) non uniform radio signal strength that varies depending on the direction, 4) wireless propagation effects (fading and multi-path), 5) interference due to hidden terminal problem, and gray area. Needless to say, sensor networks are greatly affected by the deployment environment, and the behavior of wireless communication is highly unpredictable under different environments.

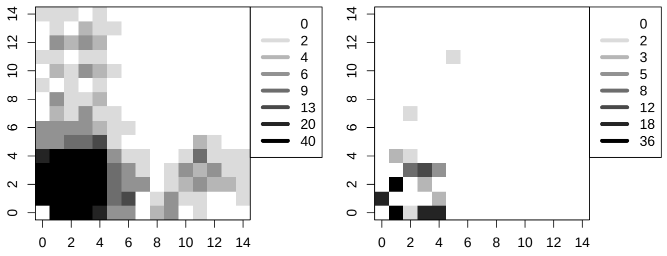
In spite of such anecdotal evidence of poor packet delivery performance, most of the designs typically assume 1) low bit error rates and consequently low packet loss, 2) 802.11-like links that avoid hidden terminal problems, and 3) generally reliable wireless communication. Even though such assumptions may become a reality in the future with advances in hardware technology, many challenges will still remain. For example, even with advances in hardware, smaller footprint devices such as today's motes are desired, despite being resource constrained. The deployment of sensor networks in harsh environments deteriorates the quality of wireless communication. Various propagation effects and high packet loss are expected in such environments.

There exists a large body of work in the area of MAC protocols [9]–[11], [14] and routing protocols [3]–[5] that deal with issues such as power conservation, hidden terminal problem, congestion, and fairness. Some of them assume CDMA (code-division multiple access) or TDMA (time-division multiple access) that require multiple channels and/or time synchronization. The high resolution time synchronization requires a high overhead of control message exchange. Since message transmission may overlap in an unplanned manner, periodic corrections may be required. CSMA is widely used in contemporary sensor network hardware such as Mica and Mica2 motes. Therefore, it is important to understand what precludes reliable packet delivery in current field trials.

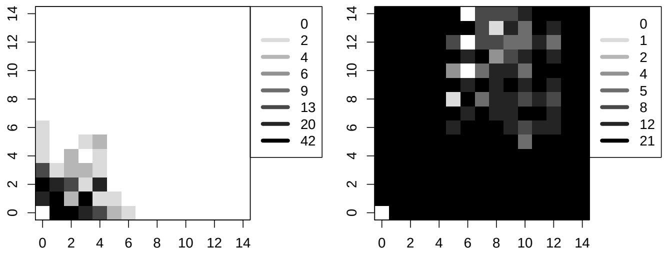
The underlying MAC paradigm used in the study is CSMA that is common due to its simplicity and low overhead. The study is carried out using the TOSSIM simulation framework for a Berkeley Mote based system. TOSSIM has some limitations such as pessimistic radio model. However, we use TOSSIM in our study since it allows TinyOS code to be run as is, and simulates lossy channels using an empirical model. The primary contribution of this paper is a set of protocol independent enhancements for boosting the packet delivery rates and fairness for all-to-one communication in dense sensor networks.

Specifically, we make the following contributions:

1) We have quantified the performance impact of various factors that affect packet delivery performance and fairness including:
    - Acknowledgements
    - Message buffering
    - Bit errors in the links
    - Encoding schemes for data packets
    - Radio transmission range



(a) Flooding Routing (b) AODV Routing



(c) Geographic-baseline (d) Geographic routing with enhancements

Fig. 1. Reliable packet Delivery Pattern: 225 Nodes

2) We have shown through a simulation study that such enhancements are additive.
3) Concretely, we have shown that using Geographic routing in a WSN with 225 nodes spread over 150 feet x 150 feet, the proposed enhancements yield a 23-fold improvement in packet delivery performance over the baseline. Further, the enhancements result in fairness (measured by the number of messages received from each node at the destination). We also show that the overhead (in terms of retransmissions, acknowledgement messages, and control messages) is reasonable.

The rest of paper is organized as follow. Section II presents our hypotheses regarding the factors that limit performance as well as our proposed enhancements for overcoming them. We present the framework for our performance study in Section III, followed by the performance results in Section IV. We present the lessons we learned in Section V and related works are reviewed in Section VI. We discuss future research direction and conclude in Section VII.

II. LIMITING FACTORS AND PROPOSED ENHANCEMENTS

While we get much more into the details of the simulation results in later section, it is worthwhile considering the result from an example experiment to explain the problem being studied. The experiment uses TinyOS MAC layer in TOSSIM to quantify the many-to-one packet delivery performance for three protocols: flooding, AODV, geographic routing.

In Figure 1, each square in the grid represents a Berkeley mote. The mote at the bottom left corner is the destination and all the others are sensors sending packets at an uniform rate to the destination. The darkness is an indicator of successful delivery of packets from that node to the destination. What we would like to see is a uniformly dark graph. However, the results are far from this expectation as can be seen in Figures 1(a), 1(b), and 1(c):

1) A significant packet loss is experienced with the success rate for data delivery rapidly decreasing for the distant nodes.
2) Flooding does relatively better than the other two as long as packet delivery is concerned, but incurs a significant overhead (not discernible from these figures) due to the nature of the protocol.

The bottom line from this simple experiment is that the performance (92.6% packet loss for flooding, 98.8% for AODV, and 97.7% for geographic routing) is nowhere near what may be acceptable in a typical deployment. These results raise two related questions:

1) *What are the contributing limiting factors for poor packet delivery?* In the rest of this section we hypothesize factors that could be leading to such poor performance.
2) *What can be done to improve the packet delivery performance?* One could take one of two approaches to answer this question. One approach is to a holistic approach and undertake a complete redesign of the protocol stack [12] including perhaps new MAC protocols (along the lines of proposals such as [9], [11]) with appropriate hardware support. In this paper we take a second more evolutionary approach. After identifying the factors leading to poor packet delivery, we suggest incremental enhancements to the protocol stack that can alleviate the performance problems. Such enhancements are presented in this section as well. The advantage of this approach is that the current deployments of sensor networks that use Mica and Mica2 can immediately benefit from such enhancements. Moreover, these enhancements are not protocol-specific. In Section IV, we quantify the improvement to the performance attained by each of the proposed enhancements.

The good news is that cumulatively, the proposed enhancements get us close to an acceptable level of packet delivery performance as can be seen for geographical routing in Figure 1(d).

A. High Bit Error Rate (BER) in Received Packets

Bit errors in received packets due to noisy wireless medium is one source of packet loss. Forward error correction (FEC) is a commonly used technique to reduce the effects of bit errors. The default encoding in TinyOS MAC is "single error correction double error detection" (SECDED) in which each byte is encoded into a 24-bit word. If e is the bit error rate, k is the number of bits in the encoded, and e_c is the maximum number of bit errors that can be corrected, then the probability of successful delivery of one source byte (24-bit encoded word) is:

$$p_{success} = \sum_{i=0}^{e_c} \binom{k}{i} (1-e)^{k-i} e^i$$

For example, with SECDED, when bit error rate is 0.01, $p_{success} = \sum_{i=0}^{1} \binom{24}{i} (0.99)^{24-i} 0.01^i \approx 0.976$. One packet in our simulation is 24 bytes including 2 bytes CRC. Given this, the probability of successful delivery of one packet is $(p_{success})^{24} \approx 0.558$. A lossy radio model generator in TOSSIM based on empirical data shows up to 0.05 bit error rate, which results in a probability of successful packet delivery of only 4.8×10^{-5}. Such poor packet delivery is not acceptable in sensor network deployments.

Therefore, our first hypothesis is that packet corruption (due to bit errors) is a significant limiting factor. To verify this hypothesis, we first isolate the contribution of packet loss due to bit errors. We then propose to use *DECTED* (double error correction and triple error detection) [6] as a way of reducing such packet corruption and evaluate its positive influence on packet delivery.

B. Choice of Routing Protocol

There are a number of routing protocols proposed in the literature. (Directed diffusion [5], SPIN [4], and SPEED [3]) are examples specifically targeted to sensor networks. Protocols that have been proposed for MANETs (such as AODV, DSDV, and DSR) may also be adapted for use in sensor networks. Each protocol has its advantage and disadvantage depending on the communication pattern in the application. For example, Directed diffusion and SPIN are designed to reduce the amount of data with query based communication, but its behavior will be the same as all-to-one communication when the query requires sensing data from all area with a constant duration. Our study focuses on all-to-one communication where protocols proposed for MANETs are more suitable due to the communication pattern. Moreover, all protocols will suffer from a reliability issue in WSN. For our study, we picked simple Flooding, AODV [8], and Geographic routing. There are some nuances to adapting AODV and Geographic routing for use with sensor networks.

Flooding, one of the simplest routing techniques, is perhaps impractical due to its high overhead owing to the redundancy in the forwarded messages, but is expected to have good packet delivery performance for the same reason. AODV is considered one of the best candidates in the MANET space. Geographic routing can take advantage of location information in routing decisions. Our second hypothesis is that Flooding will do better than the other two in terms of packet delivery performance while the overhead is high.

C. Lack of Message buffering

Buffering messages and dynamic allocation of buffer space in the presence of congestion or burstness in traffic is a common technique in Wired and Wireless LANs. However, due to their resource constrained nature such techniques are not usually employed in WSNs.

Our third hypothesis concerns message buffering. It is fairly intuitive that providing buffering in the nodes will help with packet delivery performance. Our intent in this regard is to answer the following question: *How large a buffer do we need to maintain with a given network size and workload*?

D. Traffic Density

Our fourth hypothesis ia derived from the face that the packet delivery performance is closely related to the workload presented to the WSN. In a more demanding application such as disaster recovery perhaps a more aggressive data generation rate may need to be supported. Since our focus is on understanding the limits to packet delivery, we intentionally perform stress test with high packet generation rates. In our simulation set up, we evaluate the relationship between workload and reliability by varying packet generation rates.

III. PERFORMANCE STUDY

We decided to use a simulation framework to understand quantitatively the limits to packet delivery performance detailed in Section II. There are pros and cons to using a simulation framework. Real deployments capture environmental effects such as radio interference more faithfully. However, a simulation-based study gives rapid quantitative answers to questions on design choices. We have implemented the three protocols (Flooding, AODV, and Geographic routing) within a simulation framework, as well as the protocol enhancements discussed in Section II.

The candidate platforms we considered for our simulation study included TOSSIM, ns-2, and GloMoSim. Of these three, TOSSIM closely models the hardware platforms used in current day sensor networks. It is a simulator for TinyOS applications running on Berkeley Mica motes that are widely deployed in field trials. Therefore, the results from TOSSIM is expected to be very much in line with observations from field trials.

TABLE I
SIMULATION CONFIGURATION

Parameter	Configuration
Routing	Flood, AODV, Geographic
Buffer Size	1,2,4,and 16
Acknowledge	With ACK and without ACK
Encoding Data	No encoding, SECDED and DECTED
Max. TX Range	50 feet, 22 feet
Traffic Density	1 packet every 5s, 10s, 20s, 30s
BER	default, 20%, 80% improvement, noise-free
Nodes	4–225 nodes (14 different set)

TABLE II
LEGEND OF ROUTING PROTOCOL ACRONYMS

AODV	Ad-hoc On-Demand Distance Vector
Flood	Simple flooding
SF-20	Selective Flooding [a] with 20% probability
SF-50	Selective Flooding with 50% probability
GL	Geographic Location-based routing
GL-ACK	Geographic routing with ACK

[a] We associate a flood probability. The probability values yield a selective flooding policy to reduce the overhead.

Table I summarizes the parameters used in the simulation. The workload is all-to-one (the destination is at the bottom left corner of the grid). Such a workload is quite common: monitoring the distribution of temperatures in a volcano to forecast eruptions; and developing contour maps of different parameters in a geographical area. Note that data aggregation, a popular technique used in sensor networks to reduce message transmissions, is not useful for such a communication pattern. Further, data from all nodes are equally important to get the global picture needed in the application.

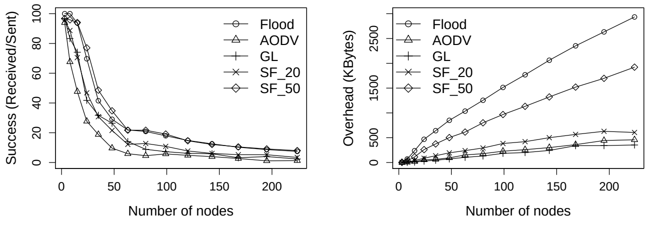
The number of retries before a sender gives up is set to be 10. A data packet is 24 bytes including CRC, and the total simulation time is $600s$. Fundamentally the topology simulated is a grid: one node is placed randomly inside a 10 square feet area; the average distance between any two neighboring nodes is 10 feet. We use a constant generation rate (e.g n packet per second) for each node.

IV. RESULTS

Successful packet delivery is the primary performance metric used in the evaluation since that is the focus of this study. A related metric is the *overhead* (in terms of retransmissions, acknowledgement messages, and control messages for route discovery) that has a direct bearing on the energy consumption of the sensor network. *Fairness*, as measured by the distribution of successful receptions from all the nodes is another figure of merit that is important for this study. Metrics such as latency and throughput, while extremely important, are not the focus of this study.

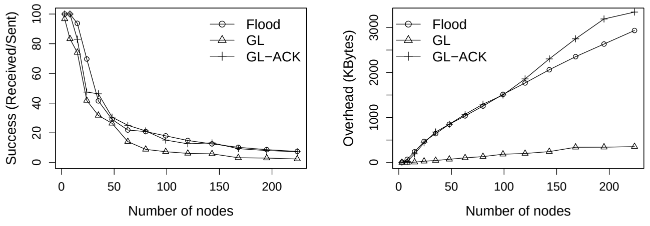
A. Impact of Routing Protocol

Figure 2 shows the packet delivery performance and overhead for flooding (and its variants), AODV, and Geographic routing. The x-axis represents the number of nodes in the grid; for the success rate graph the y-axis represents the overall success rate, i.e., the ratio of number of messages received



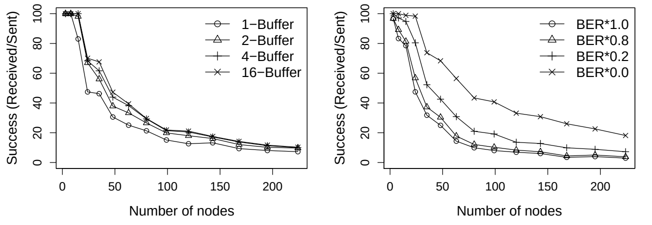
(a) Successful Delivery Rate (b) Overhead (KBytes)

Fig. 2. Different routing protocols

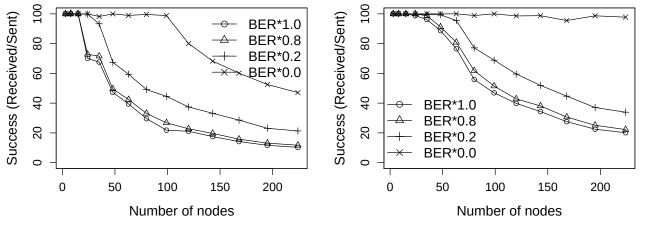


(a) Successful Delivery Rate (b) Overhead (KBytes)

Fig. 3. No Acknowledgement vs. Acknowledgement (1-message buffer): Overhead is the total amount of data that transmitted but not delivered.

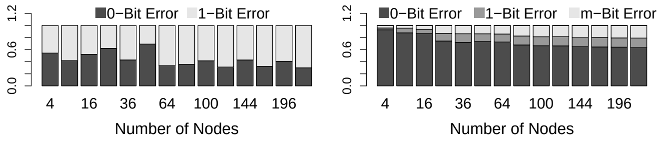


(a) GL with ACK message (b) GL without ACK



(c) GL-ACK (d) GL-ACK (0.03 pps)

Fig. 4. Successful Delivery Rate: (a)Different message buffer size; (b)–(d):Bit Error Rate variation: 16-buffer



(a) CRC passed packets (b) CRC failed packets

Fig. 5. Received Packet: Geographic routing, 0.1 packet per second (pps), 16-Buffer, SECDED

to those sent for a particular configuration of the grid; for the overhead graph the y-axis represents the overhead which is the total amount of transmitted bits (including control, forwarding, and retransmissions) minus the message bits successfully received in the entire run for a particular configuration of the grid.

Table II gives the acronym and the protocol it stands for in this and other figures in the rest of this section. As expected, flooding does relatively better than the other protocols in successful packet delivery (Figure 2(a)). But this comes at a high overhead (Figure 2(b)). However, the performance is nowhere near acceptable. For example with 100 nodes, the success rate for Flood is around 18%, while it is 7.3% and 5.8% for Geographic and AODV routing, respectively.

B. Impact of Acknowledgements

Figure 3 shows the impact of acknowledgement message on geographic routing. The success rate improves with acknowledgement messages. With 100 nodes, the success rate for geographic with acknowledgement (the curve labeled GL-ACK) is 15.1% which is quite close to flooding. However, it should be noted that the overhead has gone up as well (see Figure 3(b)). With acknowledgements, the nodes try harder (via retransmissions) to route the messages to the destination. Further, as the grid size increases more nodes within a transmission range are competing for air space to send to the destination.

C. Impact of Buffering Messages

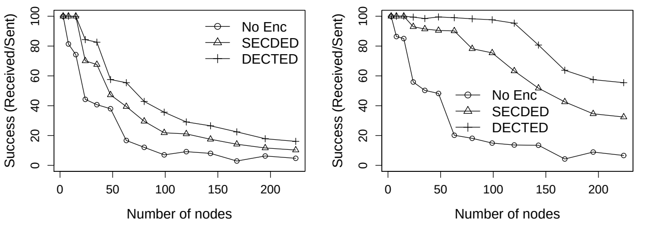
We hypothesized that increasing the buffering at each node will improve the success rate. Figure 4(a) confirms this hypothesis. For example, with 100 nodes using 2 buffers instead of 1 improves the success rate from 15.1% to 19.9%; 16 buffers improves it to 21.9%. Note, however if ACKs are not used the additional buffers have little impact since the nodes do not have to hold the packets for retransmissions.

D. Impact of Bit Error Rate

The results in this subsection quantify the effect of bit errors on packet loss. Figures 4(b) and 4(c) show the impact of varying the bit error rates on successful packet delivery without and with ACKs, respectively. Interestingly, it is observed that even with error-free links, without ACKs (Figure 4(b)), the packet delivery rate is less than 22.6% with a grid size of over 200 nodes. Employing ACKs improves the performance considerably (Figure 4(c)). The dip in performance beyond 100 nodes with error free links in this figure is mainly due to the offered workload. Even with 16 buffers, the traffic density is not sustainable (due to interference among the nodes) since it most likely violates Little's result [7]: $\rho = \lambda/\mu > 1$ where λ is the arrival rate of a packet at a node, and μ is the service rate. Figure 4(d) confirms this hypothesis, wherein we have reduced the offered load of each node to 0.03 packets per second. With error-free links we can see almost perfect success rate with this reduced workload.

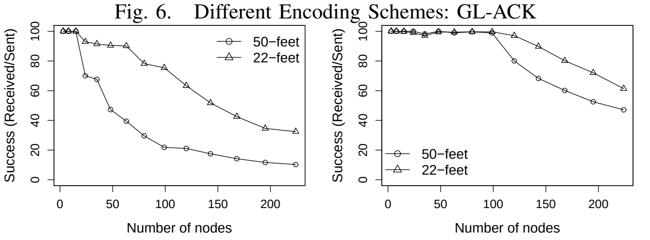
E. Impact of Encoding Schemes

We now turn our attention to analyzing the reason for packet loss in the presence of noisy links and interference among the nodes. It is precisely for this reason that TinyOS implements the SECDED encoding on data packets. Figure 5 shows the number of packets passed CRC, and those that failed CRC in the SECDED encoding regime. As can be seen, the number of packets passing CRC (upon successful reception) is less than 20% when there are more than 200 nodes. We dissected the received packets to understand the effectiveness of the SECDED encoding. As can be seen in Figure 5(a), more than 50% of the packets that passed CRC were repaired by the 1-bit error correction of SECDED. On the other hand, looking at Figure 5(b), we can see that among the packets that did not pass CRC, over 82% of the received bytes in a given packet are decoded correctly. Yet, the packet had to be discarded because the remaining bytes in that packet had more than 1-bit error. When a bit error rate is high, the benefit of single error



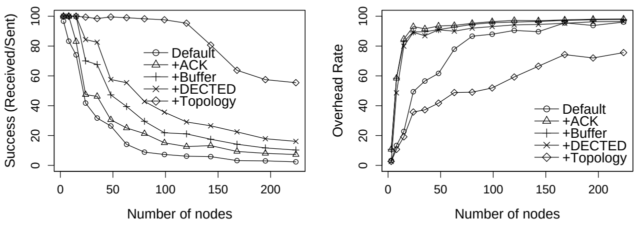
(a) Successful Delivery: 50-feet tx range (b) Successful Delivery: 22-feet tx range

Fig. 6. Different Encoding Schemes: GL-ACK



(a) Realistic Environment (b) Noise-free links

Fig. 7. Different Transmission Range: 0.1 packet per second (pps)



(a) Success Delivery (b) Overhead Rate

Fig. 8. Delivery rate and overhead with improvements: Overhead rate is $\frac{\mathrm{msg}_{\mathrm{overhead}}}{\mathrm{msg}_{\mathrm{overhead}}+\mathrm{msg}_{\mathrm{delivered}}}$

correction is low. Not only does it reduce a channel utilization, but also it degrades the overall performance.

While DECTED encoding did not help ACK packets, we postulate that it will help data packets. While it is intuitive, we quantify the impact of encoded data packets. Figure 6(a) shows the success rate for no encoding, SECDED, and DECTED encoding confirming this hypothesis. For 100 nodes, DECTED encoding is nearly 63% better than SECDED.

F. Impact of Transmission Range

The default radio transmission range assumed by TOSSIM is 50 feet. When the transmission range is large, smaller number of hops are sufficient to route a packet. This helps point to point packet delivery. However, for all-to-one communication in a dense wireless sensor network, increasing transmission range incurs 1) high energy consumption in each node, 2) heightened contentions among neighbors, and 3) increased probability of hidden terminal problem. These factors band together to both reduce reliability as well as increase energy consumption. Even though decreasing the transmission range can result in higher bit error rate, the reduced contention and interference are likely to increase reliable packet delivery. To test this hypothesis, we conducted simulation with two different radio ranges 50 feet and 22 feet. The results shown in Figure 7 (for both realistic and idealized links) confirms our hypothesis. For example, with 100 nodes (see Figure 7(a)) the smaller transmission range achieves a success rate of 75.4% while the larger one achieves only 21.9%.

Further, the reduced transmission range aids encoded data transmissions considerably. As can be seen in Figure 6(b), both SECDED and DECTED gain due to the reduced transmission range. For example, with 100 nodes, SECDED achieves a success rate of 75.4% and DECTED achieves a success rate of 97.6%.

G. Putting Them All Together

In this subsection, we bring together all the individual enhancements we discussed in the preceding subsections. Figure 8 shows the effect of adding each enhancement to the baseline performance of geographic routing. The reader may recall that the baseline performance (labeled Default) uses SECDED encoding for data packets and no acknowledgements. By adding acknowledgement, on the average, the packet delivery performance is twofold better than default. Adding a 16-element message buffer at each node adds another mean improvement of 29.8%. For small number of nodes this enhancement does not offer much advantage for obvious reasons. However, in the best case, the improvement is 95% with 120 nodes. An additional improvement of 20%-63% is achieved with DECTED encoding. On an average, the reduced transmission range enhancement adds another 112% improvement. Thus the cumulative improvement of all these enhancements over the default configuration is tenfold on the average, with the best case being 23 times better than baseline for 225 nodes.

Figure 1(d) shows the same result visually over the entire grid. It can be seen that not only is the reliability increased tremendously by these enhancement but also the fairness, since most of the nodes are able to get their packets delivered to the destination node.

V. LESSONS LEARNED

We started this research as a simple exercise in trying to understand the applicability of MANET-style wireless protocols to dense wireless sensor networks. We focused on all-to-one communication pattern since that is a dominant one in many sensor network applications. We were initially dismayed to find that the packet delivery performance of well-known protocols were so dismal in such a setting. However, a closer analysis of what is going on under the covers led to several useful insights that led to dramatic improvement in performance.

While the bulk of the results section focused on geographic routing to demonstrate the performance improvement accrued from the proposed enhancements, most of these enhancements apply in a straightforward manner to other routing protocols such as AODV and even flooding. For example, in the case of AODV, on the average, acknowledgements improves the performance by 68% compared to the baseline; and buffering improves performance by another 60%.

Since our study was limited to all-to-one communication pattern, we do not have anything definitive to say about other communication patterns. However, we can make some general observations. If some sort of clustering is used in the sensor network, then the protocol used for the many-to-one communication to the cluster heads stands to benefit from the proposed enhancements.

There are several important lessons that we learned as a result of this work:

1) The first lesson is that it is feasible to get good success rates and fairness for packet delivery with fairly modest changes to the mechanics of the routing protocol implementation.

2) Further, these enhancements are additive in nature. In fact, the sum total of performance gains, as it turns out, is greater than the parts because of second order effects such as reducing contention and interference.
3) These enhancements are not protocol-specific and can co-exist with most existing protocols for sensor networks.
4) The enhancements do not depend on any new hardware or changes to the basic CSMA-based MAC protocols currently used in Mica-2 based sensor network deployments.
5) Perhaps the most important lesson is that achieving good packet delivery performance is feasible without a drastic change to the protocol stack or the hardware architecture of sensor networks.

It is useful to prioritize these enhancements from a cost-benefit perspective in decreasing order of importance for improving the performance. We would order the enhancements proposed in this work as follows to improve performance:

1) Using hop-by-hop acknowledgements
2) Using multiple message buffers at each node
3) Using a robust error correction scheme for data packets
4) Using differential transmission ranges on the radio commensurate with the density of the sensor network.

VI. RELATED WORK

Perhaps the first study to extensively evaluate performance in terms of packet delivery is the one due to Zhao *et al.* [15]. In their work with 60 motes, they show that a third of the links experienced more than 30% packet loss. They also show 4-bit/6-bit encoding is more bandwidth efficient when packet loss rates are less than 50% while SECDED has a lower incidence of high packet loss. Their study is empirically based and uses a linear topology of Berkeley motes. While such empirical studies are valuable, they do not lend themselves easily to ask "what if" questions relating to protocol design and their performance impact. Our study being simulation-based using TOSSIM allows us to both understand the factors that limit performance in dense wireless sensor network, as well as answer many "what if" questions.

Packet combining [1] also addresses reliability issue, and it merges packets with overheard packets. With promiscuous listening, burst errors due to multi-path fading can be minimized using this technique and overheads due to retransmissions can be avoided. However, in a harsh environment, it may have less chance to overhear such packets. TRAMA [13] is a schedule-base medium access protocol. Even though the main goal of their work is not reliable delivery, they show that a schedule-based protocol outperforms contention based one (e.g. CSMA.) However, maintaining time synchronization that is required for schedule-based MACs, has non-trivial overhead.

While congestion control schemes [2] have a different focus than ours, there are elements of commonality in that they also strive to ensure fair and reliable packet delivery for most of the nodes. For example, Ee *et al.* [2] propose using back pressure on generating nodes by counting the number of receiving nodes for packets from a given source node.

VII. CONCLUSION AND FUTURE RESEARCH

Sensor networks bring an interesting confluence of systems and networking issues. They share a number of characteristics with MANETs, however, they differ significantly in many dimensions. Some of the significant differences are the density of the nodes as well as the traffic generated by the nodes. Equally important differences are the platforms used and the deployment environments. In this paper, we undertook a study of reliable packet delivery in dense sensor networks for an all-to-one communication pattern. We first identified potential limiting factors for successful delivery and postulated protocol enhancements to circumvent them. Using TOSSIM, we carried out a systematic study to quantify the factors that limit achieving good performance in such a setting. We then showed how the proposed enhancements, most of which are protocol neutral, can boost the performance to acceptable levels. For example, for a 225 node sensor network deployed in a 150 feet x 150 feet grid, the enhancements cumulatively boost the performance by 23 times compared to a baseline using geographic routing.

Currently, these enhancements along with the parent protocols (geographic routing, AODV, and Flooding) have been implemented as modules in the TOSSIM framework. Our future work includes implementing these enhancements on top of TinyOS on Mica-2 platforms. Such an effort will shed new light on the efficacy of these enhancements, as well as reveal new insights for controlling radio transmission ranges.

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