Event Reliability in Wireless Sensor Networks

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***Abstract*—Ensuring reliable transport of data in resource constrained Wireless Sensor Networks (WSNs) is one of the primary concerns. The two reliability mechanisms typically used in WSNs are *packet* reliability and *event* reliability. *Packet* reliability requires all packets from all the sensor nodes to reach the sink that can result in wastage of sensors' limited energy resources. The sensing regions of densely deployed sensor nodes often overlap with one another and data from nodes that are in close proximity tend to exhibit high level of spatial locality. This introduces the concept of *event* reliability where a reliable transfer of event data from each sensing region in a sensor network is sufficient. This paper proposes the *Event Reliability Protocol* (ERP) that enables reliable transfer of packets containing information about an event to the sink while minimizing similar redundant packets from nodes in the vicinity of one another. ERP builds on the spatial locality condition and employs an implicit acknowledgement (iACK) mechanism with region-based selective retransmissions. The performance of ERP is evaluated and compared against a commonly used *iACK* scheme to show that ERP significantly improves event information delivery and network scalability, thus maintaining good coverage of events in the sensor network.**

Index Terms - Wireless Sensor Networks, Reliability, Acknowledgments

I. Introduction

Wireless Sensor Networks (WSN) typically comprise a large number of low cost and small sensor nodes used to monitor physical conditions in an area. The nodes then performs in-node processing and route the data towards sink [1][2]. Due to the resource constrained nature of an individual sensor node, a collective effort is needed from sensor nodes in the network to accurately monitor a large area and deliver the significant information to the sink. Critical data collected by the sensor nodes need to be reliably delivered to the sink. Therefore, given the nature of error prone wireless links, ensuring reliable transfer of data from resource constrained sensor nodes to the sink is one of the major challenges in WSNs.

Most of the research has been done to ensure traditional *packet* reliability where all the packets carrying sensed data from a sensor node needs to be reliably transported to the sink. Due to the error prone wireless links, packet loss may occur and thus *end-to-end packet* reliability requires every packet to be acknowledged and each lost packet to be retransmitted. These unnecessary retransmissions and acknowledgements increase the packet transmission overheads and creates network congestion. However, comparatively fewer works have focused on *event* reliability where packet loss can be tolerated as long as the sink receives at least one packet containing the sensed data of an event; therefore, event reliability does not require the retransmissions of every lost packet. This reduces the unnecessary retransmissions by requiring the network to transmit only a single packet from one node among a number of closely located nodes that have sensed the event.

In a multi-hop WSN, to achieve reliability in general, data packets need to be acknowledged by the next hop neighbouring node that is relaying them through to the sink. The two major kinds of acknowledgement schemes are explicit acknowledgement (eACK) and implicit acknowledgement (iACK). The *eACK* mechanism is used to ensure the absolute reliability guarantee for every single packet transmitted. In *eACK*, after the receiving node successfully receives a packet, it explicitly sends an *eACK* back to the sender as a receipt of the sent packet. However, this results in high transmission overhead and energy wastage in an error prone environment like WSNs. On the other hand, the alternative *iACK* mechanism exploits the broadcast nature of wireless channel without incurring any additional transmission overhead. The sender, after transmitting the packet, listens to the channel and interprets the forwarding of its sent packet by the next hop node as a receipt of acknowledgement [3]. In a wireless network, *iACK* mechanism performs better than *eACK* in terms of reducing the packet overhead, energy efficiency and provides better *hop-by-hop* reliability [4][5].

In WSNs, *event-to-sink* reliability as opposed to *end-to-end packet* reliability is sufficient for most of the event driven applications. Reliability in this way means that the sink will be notified of all the events happening within the network. In the light of this, we propose the *Event Reliability Protocol* (ERP), an *event-to-sink* reliability protocol that serves to improve the scalability of event detection in a WSN by minimizing the unnecessary retransmission of data packets coming from multiple nodes in an event's locality. ERP takes advantage of the broadcast nature of wireless channel by using an *iACK* mechanism with region-based selective retransmission of packets.

The rest of the paper is organized as follows. In Section II, we study the existing approaches that serve to manage the data transfer reliability issues in WSNs. The proposed protocol is described in Section III. In Section IV, we evaluate ERP using simulations and compare its performance with that of the Stop-And-Wait with Implicit Acknowledgement (SWIA) approach used by the Directed Flood-Routing Framework (DFRF) [3]. This paper is concluded in Section V where some of our possible future work is also presented.

II. Related Work

The various reliability protocols for WSNs can be divided into two general categories: packet reliability and event reliability. *Packet reliabililty* aims to ensure the delivery of every data packet to the sink while *event reliability* aims to ensure that at least one of many packets from the sensors that detected an event is delivered to the sink. We will provide a brief discussion of event-reliability protocols, which is by no means comprehensive; wider surveys of different reliability protocols for WSNs are available in [6] and [7].

The most notable event-reliability protocol is *Event-to-Sink Reliable Transport* (ESRT) [8]. It guarantees only the delivery of individual event information to the sink, not individual packets from each sensor node. It ensures reliability by redundancy. When the required reliability is not achieved, the sink will increase the event reporting frequency (f) at the sensor nodes. Conversely, it will reduce f when there is congestion in order to bring back the reliability required at the sink. In the event that the required reliability is observed at the sink, it will decrease f to reduce the nodes' energy consumption. A key assumption of ESRT is that the sink has high power radio that can transmit the latest f value to all sensor nodes in a single broadcast message.

ESRT addresses event reliability but not congestion control explicitly. STCP [9] which is a generic upstream (sensor-to-sink) transport protocol provides both event reliability and congestion control. The sink is notified of congestion in the network by intermediate nodes using a *congestion notification* bit in packet headers which they set based on their queue lengths. The sink will then notify the affected source nodes of the congested paths and to find alternative paths for their packets.

Like STCP, the *Price-Oriented Reliable Transport* (PORT) [10] protocol also aims to provide finer fidelity in event reliability (as compared to ESRT) while minimizing energy consumption. Unlike ESRT which uses a network-wide reporting rate, PORT uses source-specific reporting rates and aims to avoid high loss rate paths. To achieve the source-specific need, PORT assumes that the sink is aware of the information contained in packets.

ART [11] also provides *end-to-end event* reliability by creating a set of E-Nodes (also known as essential node) that covers an event area. The *ACK/NACK* based upstream and downstream reliability in ART depends on the E-nodes. This introduces extra session initialization delay and creates high packet overhead.

More recently, the *Loss-Tolerant Reliable Event Sensing* (LTRES) [12] protocol has been proposed for sensing applications with heterogeneous sensing fidelity requirements over different event areas. LTRES addresses event-to-sink reliability by guaranteeing the end-to-end transport reliability requirement of an event area instead of from each sensor node. It also provides network capacity awareness by measuring the event goodput observed at the sink and aims to adapt the source rates based on network capacity. Instead of relying on nodes to detect and report congestion to the sink, LTRES employs a sink-based congestion detection algorithm and suppresses the rates of aggressive source nodes.

Most, if not all, existing schemes rely on the sink to impose some form of control over the flow of data in the network, and a reliable downstream (sink-to-sensor) communication mechanism has been assumed. Our proposed scheme, ERP goes away with the sink centric approach by introducing in-network data processing, where the data packets are being pre-processed at the nodes before forwarding them further. This in-node processing reduces the transmission of unnecessary packets and saves the overall network cost in terms of energy, congestion and data flow [13].

In addition, only a few reliability mechanism for WSNs exploit the broadcast characteristic of wireless channel by using iACKs. DFRF [3] is one of the first WSN schemes to exploit iACKs. Like DFRF, Reliable Bursty Convergecast (RBC) [14] utilizes iACKs to guarantee reliability for a large burst of traffic. RBC uses employs a window-less block acknowledgement scheme to improve channel utilization while ERTP [15] proposes a dynamic retransmission timeout mechanism for iACKs.

III. Event Reliability Protocol

Keeping these issues in mind, we aim to build a more scalable and reliable event-driven wireless sensor network for monitoring application. We combine the benefits in distributed in-network processing with implicit acknowledgements and a region-based retransmission strategy.

A. ERP Overview

In WSNs, a large number of densely deployed sensor nodes continuously send the data packets towards the sink. Typically, these data packets from the sensor nodes start converging towards the sink which often results in congestion and thus packet loss occurs. To achieve *event* reliability such that only those packets carrying unique information about a particular event should reach the sink, while minimizing congestion becomes a challenging task. Besides losing packets through transmission errors, packets are also lost from signal interference when multiple nodes within range of one another transmit simultaneously. Retransmitting every lost packet can aggravate this condition.

The event data from closely located sensor nodes in a network tends to be highly correlated. This allows us to selectively tolerate packet loss instead of aiming to achieve full *hop-by-hop packet* reliability. On this basis, we design the Event Reliability Protocol (ERP) that aims to enhance *event* reliability by avoiding the unnecessary retransmissions of lost packets which can aggravate the network congestion.

To avoid the unnecessary retransmissions of lost packets, we introduce an intelligent region-based selective retransmissions mechanism based on *iACKs*. This mechanism will retransmit the lost packets only on a condition that another packet from the same region of the lost packet is not present in the node's queue. Our scheme uses a distributed approach where, instead of relying on the sink for centralized decision making, we use in-node processing that allows simple node-level decisions to be performed more efficiently.

B. Network Design

We model our network as a typical homogeneous large scale WSN having a set of sensor nodes $\{S = s_i \mid i = 1, 2, \ldots, N\}$ and a sink; where the sensor node identifiers (IDs) are defined globally, represented by i. Upon sensing an event, a sensor s_i generates packet containing event data and transmits it to the sink through intermediate nodes. The nodes are randomly deployed and routes are computed for the entire network by a WSN routing algorithm. The nodes do not need global knowledge about number of nodes and network area. We consider an event driven application with a flat network topology, where all the sensor nodes are equal in terms of their sensing range. We assume that all the sensor nodes are placed within a finite area, where the senor nodes and sink are static in nature with the pre-configured location information. Keeping in mind the static deployment of the network, the distances between the nodes and the sensing range of the nodes are fixed.

C. ERP Design

In ERP, the event region covers all the sensor nodes having enough sensing range to detect a particular event, and the data packets coming from the same sensing region with the same event occurrence time are assumed to be highly correlated to one another. Therefore, any highly correlated packet can be considered to be redundant and thus dropped to minimize the packet overhead. ERP works as follows:

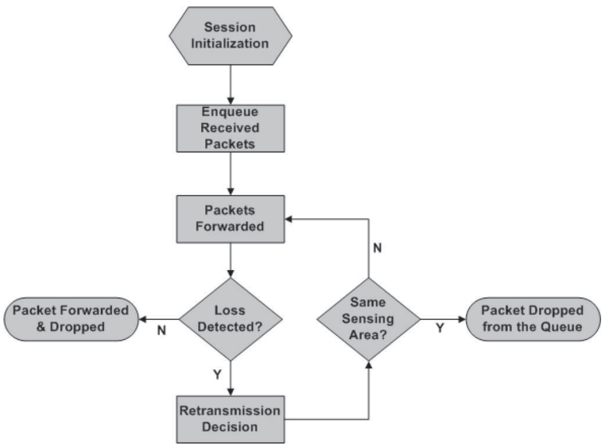

Fig. 1. Flow Chart of the ERP Operations

The ERP operations, as shown in Fig. 1, starts with the session initialization phase where the entire network configures itself upon deployment and establishes the various parameter values, such as number of nodes, packet size, network area, individual nodes' locations, routes, etc., are set up. Each sensor node will place the packets that it receives in its queue for processing and transmission. When an event occurs in the network, each sensor node in the vicinity of the event that successfully detected it puts the event information in a packet and sends the packet towards the sink. The next hop node towards the sink, after receiving the packet, places the packets in its queue and the packet at the head of the queue is transmitted to the next hop as defined by the routing protocol. When the node hears the next hop node transmitting the packet that it has sent, it is an implicit acknowledgement that the packet is forwarded successfully; the node removes the packet from (the head of) the queue and the next packet in the queue is processed. Otherwise, in case of lost packet, a retransmission decision is taken on the basis of information contained in the packet header. Each packet header contains the *location information* of the source node (that originated the packet) along with the source ID, event's time stamp (time of event detection) and the destination ID (i.e. the sink.) Finding the location of the nodes is beyond the scope of this paper but can be determined using one of the many WSN localization schemes (e.g. [16]); in this paper, locations of the nodes are assumed to be predefined and known.

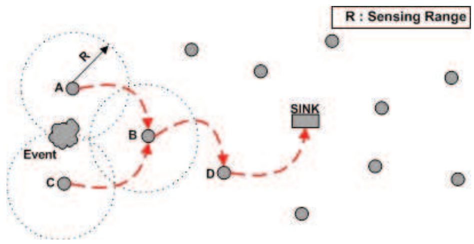

Fig. 2. Event sensing and transmission towards the sink

Suppose a random node, *A*, retrieves a packet *p* at the head of its queue and forwards it to the next hop node, *B* as shown in Fig. 2. Node *A*, sets its timer right after forwarding the packet *p* and then listens for an implicit acknowledgement from node *B*, which is the forwarding transmission of packet *p* from node *B* to the next hop node *D* towards the sink. If node *A* overhears the *iACK* from node *B* before *A's* timer expires, it means that node *B* has received and further forwarded the packet *p* towards the sink. However, if node *A* does not hear any *iACK* when its timer expires, node *A* then assumes that the packet *p* is lost.

Now, this packet loss takes us to the next phase of our scheme, that is, the region-based selective retransmission. Node *A* now has to decide whether to retransmit the packet (*p*) or not. This decision is taken by extracting the information (e.g. source ID, source location, event's time at source) from the headers of the packets currently present in node *A's* queue. The distance between the nodes, whose packets are in the queue, are calculated [16] and checked to determine whether they are in-range of one another and therefore lies within the same event's region. (Note: this is actually a conservative approach as two nodes that are beyond each other's sensing range may sense the same event, e.g. *A* and *C* which lie on opposite sides of the event occurrence.) If there exists a packet *q* in node *A's* queue that came from the same sensing area as that of packet *p* and, both *p* and *q* detected the event at the same time, Node *A* then assumes based on both temporal and spatial locality, that *q* contains data that is strongly correlated to *p's* data. Hence, we can now afford to drop the packet *p* by suppressing its retransmission with minimal loss of information.

However, if there is no such packet *q*, then we retransmit the packet *p*, and repeat the process. Meanwhile, if another packet from the same area as node *p* arrives and is added to the node's queue, then packet *p* will be dropped the next time a retransmission decision is needed. To prevent the stale packets from occupying the queue, we introduced a retransmission threshold, where the packet is dropped after retransmitting the packet up to threshold level. ERP is independent of the routing protocol and can be used to improve the event reliability and scalability.

IV. Performance Evaluation

We evaluated the performance of ERP using simulations developed on GloMoSim [17]. The area of operation in which sensor nodes are randomly deployed is *200m* $\times$ *200m*. The sink is placed at the centre of the network, located at (100, 100). We are targeting our proposed protocol for dense networks with large number of sensor nodes, and evaluated it using seven different network size configurations of 200, 250, 300, 350, 400, 450 and 500 nodes in our simulations. As we are not focusing on the routing aspect, we assume that the routes have already been computed by a routing protocol and updated in the sensor nodes. Each node has a sensing range of *10m* and communication range of *30m*. To simulate a heavily loaded network, each node periodically transmits a packet at regular intervals, which is uniformly distributed between *3sec* and *10sec*. The nodes begin transmission at simulation time *t=10sec* up till *t=3600sec*. The two-ray pathloss model is used at frequency of 2.4GHz, where the packet reception model is Signal-to-Noise Ratio (SNR) bounded with threshold of 10dB. We compare ERP with the Stop-and-Wait Implicit Acknowledgement (SWIA) mechanism used in DFRF [3] in terms of coverage with increasing node density, events successfully reported to the sink (by the packets it received), number of duplicate packets transmitted and energy consumption in terms of packet transmissions by individual nodes.

We assess ERP by how well event occurrences are reported to the sink from all over the network as compared to SWIA and no-retransmissions (as a baseline for comparison.) In the no-retransmissions scenario,

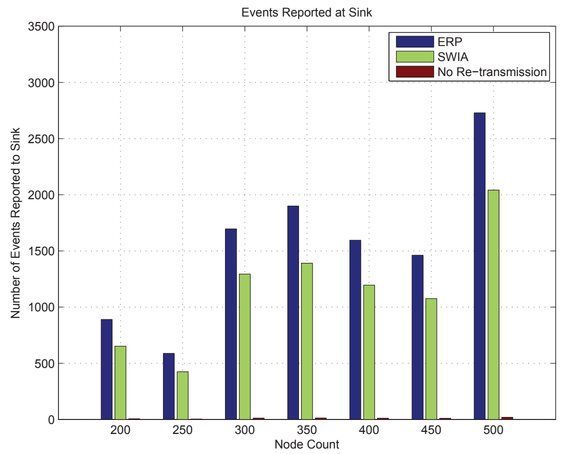

Fig. 3. Number of Event Detections Reported at the Sink

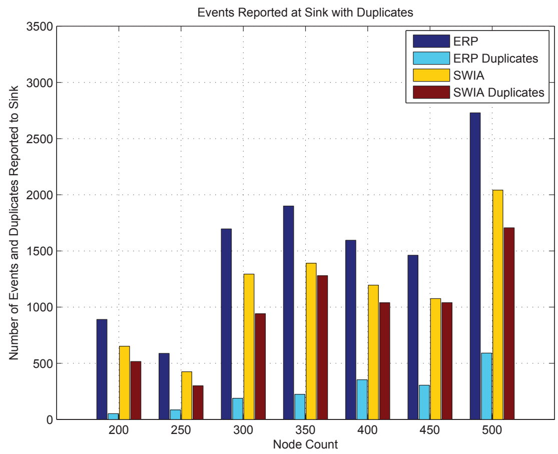

Fig. 4. Number of Events Reported with Duplicates

nodes transmit packets without considering any kind of reliability or acknowledgement mechanism. They simply forward the packets one after another without retransmitting any of the packets that are lost due to transmission errors, low connectivity, collisions or any other foreseeable reasons. In Fig. 3, we show results on the number of events detected based on the packets that have been successfully delivered to the sink. Comparing ERP against SWIA and no-retransmissions, we note that SWIA shows comparable performance to ERP in all scenarios, as node density increases from 200 to 500 nodes, although ERP performs slightly better. The dips in the results are by no means caused by the protocols themselves; rather, they due to the connectivity arising from the topology of the network.

Without a reliability mechanism, it is not surprising that only a negligible amount of events are reported. This is because, when the network is too dense the then the packets are lost due to collisions and with no retransmission mechanism in a large network, minimal amount of packets are able to reach the sink. In the case of no-retransmission, it is also observed that only the nodes are closest to the sink are able to successfully transmit the packets to the sink. These observations show how much worse a network can be, without having an efficient reliability mechanism.

The SWIA approach is simple and straightforward; it does not require the information that ERP needs for its region-based decision making. Therefore, from Fig. 3, it may be argued that the gains from ERP does not justify the effort and additional information needed. However, when we calculate the number of duplicate events reported at the sink for ERP and SWIA, as shown in Fig. 4, we can clearly see the benefits provided by ERP in minimizing the number of duplicate event packets. ERP shows much higher number of unique events reported at the sink as compered to SWIA; this is evident from the number of duplicate events reported at the sink in ERP being much lower as compared to that in SWIA. This means that the actual number of unique events reported at the sink for ERP is significantly higher. Therefore, ERP is significantly better as compared to SWIA in terms of successfully transmitting useful event information to the sink.

Energy consumption is one of the major problems in WSNs, especially in a network of densely populated sensor nodes continuously transmitting sensed data back to the sink. Since the radio communication component of sensor nodes is typically the highest power consumer, we also evaluate the energy efficiency of ERP as compared to SWIA in terms of the number of packet transmissions. We calculated the average number of packets transmitted by an individual node in the network, as shown in Fig. 5. While some nodes (like those closer to the sink) may transmit more packets than others, the average values provide an indication of how energy efficient the protocols are. The larger number of packets transmitted by SWIA is also related to the number of duplicate packets it forwards. In general, it is clear that ERP performs better than SWIA, where it is able to sufficiently reduce the transmission of duplicate events, and consequently, improve the event reliability and network scalability with increasing node density.

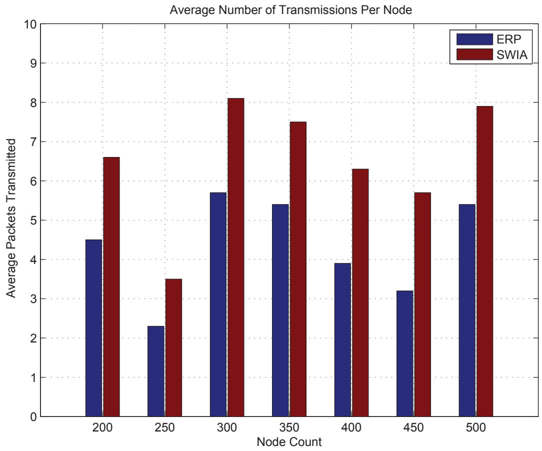

Fig. 5. Average Number of Transmissions Per Node

V. Conclusion

In this paper, we proposed the Event Reliability Protocol (ERP), a distributed *event-to-sink* reliable protocol, that provides *event* reliability in WSNs where a certain level of packet loss is acceptable as long as sufficient event information is delivered to the sink. We have evaluated several reliability protocols and noted that most of them focus on *packet* reliability rather than *event* reliability. Among the existing *event* reliability schemes, most rely on the sink to regulate the flow of data and none of them deals with the problem of declining network coverage in high level of node density. We exploited the fact that sensor data tends to exhibit high level of spatial locality and introduced a region-based selective retransmission mechanism. Furthermore, we used a distributed approach whereby, instead of relying on the sink, each node makes simple decisions using information readily available to it and do not incur additional network traffic. We have shown using simulations that our protocol significantly improves the sensing coverage of a congested network as compared to the Stop-And-Wait Implicit Acknowledgement approach, thus demonstrating ERP's potential to achieve better scalability and lower congestion.

As part of our ongoing and future work, we are designing new methods to identify packets containing duplicate event data, and a dynamic retransmission timeout mechanism to further improve the energy resource utilization. Moreover, extending ERP for use in wireless sensor networks that are powered by ambient energy harvesting [18] and also wireless multimedia sensor networks.

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