Reliable Data Delivery in Event-Driven Wireless Sensor Networks [*]

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Abstract

Protocols for sensor networks have traditionally been designed using the best effort delivery model. However, there are many specific applications that need a reliable data dissemination protocol. We present a protocol for efficient and reliable data delivery to all sensor nodes in an energy-constrained, event-driven sensor network in which nodes are mobile or static. The new protocol, SPROID (Scalable Protocol for RObust Information Dissemination), identifies data generated by a unique tag, uses content tables for faster dissemination of information and guarantees reliable dissemination to all nodes in the network within a finite time. SPROID can be made to work with any kind of physical layer requirements, but we focus on the case of a single-channel broadcast medium. Simulations results show that SPROID achieves complete data dissemination in shorter time and with more energy efficiency than SPIN (sensor network protocols using information negotiation).

1 Introduction

Networks of low-power embedded sensing devices are being used for environmental monitoring [9], and tracking and monitoring of entities in office buildings and factory fields [2]. In these applications, it may be necessary for all wireless sensors to act as sinks, so that information generated in any area of the remote monitoring field can be tapped from any node by a mobile observer, which collects information about the entire field. The key problem is to disseminate information to all the nodes in the network reliably and efficiently. We assume an application where data generation is event-driven, events are triggered sporadically, and lost events can only be refreshed when newer events get triggered. This constraint motivates the need for a reliable communication protocol, the lack of which will cause some nodes in the network to miss events. Because each node is a potential sink from which information is to be tapped, it is essential to have all nodes receiving information about all events. One such application is when a geographical area is monitored for security breaches, any event generated must be reliably disseminated to all potential sinks from which information might be retrieved. Another application is when sensors are used to monitor the break-out of fires in a building - a thermal sensor will dispatch new data informing other nodes of the increase of temperature (which indicates possible chances of fire). The mobile observer monitoring the temperatures from one set of nodes might never receive the particular temperature update if it is delivered without reliability. In this type of application, loss of an event can be critical. An example for a mobile sensor network with critical events is a disaster relief team or a mine removal team, where each entity is equipped with sensors collecting critical information about the terrain as they move. Reliable delivery of events is crucial for the members of the team to make timely decisions.

We introduce SPROID (Scalable Protocol for RObust Information Dissemination), which tags data generated with a unique identifier and provides reliable data delivery to all the sensor nodes in the network. SPROID delivers data reliably to all reachable nodes in the sensor network through a localized algorithm. The localized interaction between neighbors leads to global convergence of information generated and allows SPROID to scale independently of the network size.

The remainder of the paper is organized as follows. Section 2 provides a brief overview of the related work in the area. Section 3 describes in detail the operation of SPROID. Section 4 compares the performance of SPIN and SPROID with regard to data dissemination, scalability, and energy consumption. Section 5 provides our concluding remarks.

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2 Related Work

Wireless sensor networks are classified [3] according to their data delivery model as continuous, event-driven, observer-initiated and hybrid. Existing protocols in the literature fit into one of these data delivery models. LEACH [6] is a protocol for sensor networks with continuous data delivery and is designed for routing data to base stations in static wireless sensor networks. Other protocols that fit under the continuous delivery model include Threshold sensitive Energy Efficient sensor network protocol (TEEN) [1] and Power Efficient Gathering in Sensor Information Systems (PEGASIS) [5] which were both proposed as improvements to LEACH. In Directed Diffusion [7], data are named using attribute-value pairs and sensed information in the network can be associated with such a pair. This protocol can be classified under the observer initiated model because the the sensor nodes send queries expressing their interest for sensed information satisfying a particular criteria. The Sensor Network Protocols via Information Negotiation (SPIN) [8] are a set of protocols designed to disseminate data to all nodes in the network. SPIN fits under the event-driven delivery model in which the nodes sensing the information disseminate to other sink nodes. To our knowledge, none of the current protocols in the literature ensure guaranteed reliable delivery. We focus only on event-driven data generation and present a method to ensure complete reliability.

In this paper, we compare the performance of SPROID with SPIN, because both approaches fall under the event-driven data delivery model. Though the SPIN suite specifies protocols for different physical layer specifications, we only consider the lossy broadcast medium protocol. The protocol description of SPIN-RL is available in [8]. Hereafter, whenever we mention SPIN, we refer to the reliable version of the SPIN suite for a lossy broadcast network. We point out here the reason, the Reliable SPIN protocol(SPIN-RL) for a lossy broadcast network is unable to ensure reliability.

The performance of SPIN-RL suffers due to the lossy nature of the broadcast medium and cannot ensure information convergence at all nodes in the network. If a node happens to miss an initial advertisement due to an undelivered packet , then it is un-aware of the availability of the data item and therefore cannot request it. Consider a simple network with a four-node linear chain, where nodes A,B,C and D are sensors, each of which generate a tag for the information they sense. At a particular instant of time, A sensing new information prepares a new tag and advertises to B. B requests for the tag and receives data from A. Now B tries to advertise the newly received data tag to C, but if link BC is temporarily down due to interference then C does not receive the new tag advertisement. Nodes C and D are ignorant of the existence of such a tag unless a fresh version is generated by A. This shortcoming can be overcome by transmitting advertisements repeatedly but then it is not a scalable solution with increasing amount of data items present in the network. The major problem is that there is no limiting condition for termination of old advertisement transmission even after the information for this tag has converged throughout the network. This forms the basis for our contribution, we present a method to ensure reliable data delivery while at the same time keeping the overhead associated with reliability at a minimum.

3 SPROID

The Scalable Protocol for RObust Information Dissemination (SPROID) can use any naming scheme to identify data in the sensor network uniquely - performing a hash on the data, meta-data tags used in SPIN, or the events identified by an attribute-value pair as in Directed Diffusion. For data generated synchronously or otherwise, sequence numbers can be used within the unique identifiers to determine the freshness of data and super-cede older data. Each piece of data being generated is associated with a unique identifier tag, which we refer to as *UID* (Unique IDentifier) tag. The protocol can operate with a simple stack of an application layer utilizing the services of a MAC layer like IEEE802.11. Nodes must be identified by a unique identifier (i.e. MAC layer addresses) locally amongst neighbors. Fig. 2 illustrates SPROID's operation - nodes C and D generate data with UID tags c' and d' respectively and link CE is temporarily unavailable.

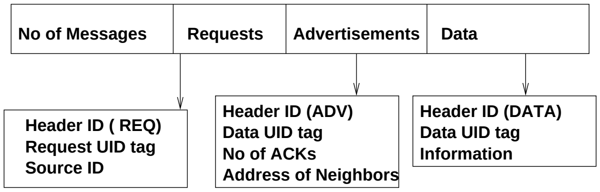


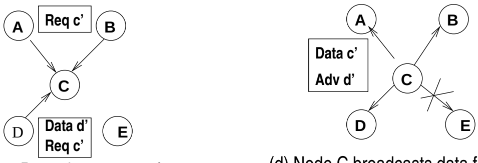
Figure 1. Content Table format

3.1 Protocol Description

SPROID uses a three-way control message handshake mechanism to exchange information and data with nodes. To achieve reliable dissemination of information to all nodes in the sensor network, the protocol relies on building an accurate neighbor list in a finite time. This is possible as long as there is a non-zero probability that all nodes within the reception range have a non-zero probability of receiving retransmissions of broadcast messages. Key features of SPROID are presented in this section.

(a) Nodes C and D sense an event at the same time , setup desynchronisation timers. D's timer expires first and sends ADV for UID tag d'.

(b) Node C sends content table with request for UID d' and also its own ADV UID tag c'. Nodes A,B and D receive ADV c' but Node E misses it



(c) Node A or B sends a request for c'. Node D sends data for d' to node C. Assuming no collisions.

(d) Node C broadcasts data for UID tag E misses the data c' . Node D notes node C's acknowledgement for d'.

(e) Nodes A,B and D broadcast ADV c'. Nodes A and B send a request for d'. Node C notes ADV as acknowledgements Node C has not received any acknowledgement from node E and requests for a ACK from node E.

(f) Node C sends out data for d' on request from Nodes A and B. Node E does not receive the packet.

g) Link to Node E comes up. E finally receives ADV for c', sends request to C and receives data for c'.

h) Node E requests for data of UID tag d' and receives it from Node C.

Figure 2. Illustration of SPROID

Depending on the radio model used in the sensors, there is usually a fixed cost associated with every data transmission and reception which implies sending many short messages will cause nodes to die quickly because of increased energy consumption. The fixed cost arises because of the transition from an idle radio state to listening or transmitting and vice versa. To keep the state transition energy consumption at a minimum, SPROID uses a communication method based on a *Content table* which is shown in Fig. 1. During an event diffusion or when the network is actively sensing changes in parameters monitored, a number of new tags will be generated. A sensor node during this time will be involved in many protocol exchanges with neighbors for data generated by itself and furnished by other nodes. Content tables provide a convenient platform through which multiple neighbors can be communicated with using a single message. This enables faster diffusion of data across multiple hops because nodes can receive control and data messages about different UID tags. This avoids the creation of hot-spots when a large number of events are detected or need to be diffused throughout the network. Content tables provide an opportunity to carry additional types of control messages without affecting normal operation. Special control messages could be used for calibration by a mobile observer or can be used to signal a special subset of nodes with more processing power to do local processing. Since each control message is identified by a type in the content table, the nodes processing the message can ignore or perform special operations.

Request messages carry the address of the node from which the data tag is requested. This is necessary to prevent collision of replies from multiple nodes with the same data or multiple copies of the data being received. But on a broadcast CSMA MAC, if a request message or the data sent by the sender node in response to the request is lost due to collisions, a request needs to be resent after waiting for a response time interval. The timeout interval needs to be selected with care since messages can be queued for transmission at the MAC layer due to the unavailability of the broadcast medium. Node A could have timed out on a request and sent another new request to node B, whereas node B transmitted the data which could be queued. This results in duplicate retransmissions resulting in unnecessary energy expenditure and causes more contention at the MAC layer. The situation could become even worse when a node effectively captures the broadcast medium resulting in more timeouts. The timer to wait for response is set as an exponential back off timer. Using an exponential back off timer prevents the nodes from timing out repeatedly when network experiences congestion or is suffering from many collisions, and allows the waiting interval to be adjusted according to the perceived local neighbor traffic. The timer is backed off on every request not answered and reset on a successful transmission. To recover graciously from advertisement messages getting lost due to packet collisions, an explicit acknowledgment scheme is used.

The explicit acknowledgment scheme presented ensures the dissemination of generated data to all nodes in the network. A sender-initiated explicit ACKing scheme is used. A node builds it neighbor list within finite time by listening to broadcast messages. The advertisement message carries a list of nodes which have to acknowledge the particular tag. Node A can tick neighbor B for a data tag if node B sends an advertisement. A request for the data tag by node B can be additionally considered as an acknowledgment, because information retrieval is receiver-initiated. The advantage of this scheme is that this fits in the normal framework of messages that nodes communicate. A node will send a request on hearing a new advertisement, or an advertisement to re-advertise the received new data. These two protocol exchanges subsume the ACKing scheme without any extra overhead. Collisions can cause extra overhead of advertisements because nodes have to retransmit when an explicit ACK is requested.

To make effective use of content tables, more information must be packed on every message exchange. A de-synchronization timer is triggered on the following events (i) receiving a new advertisement, (ii) receiving a packet which contains a request to itself, or (iii) receiving new data. During this interval, more control and data messages can be aggregated and transmitted in a single content table. The de-synchronization timer additionally helps avoiding trivial collisions caused by neighbor nodes when a node advertises new data and all neighbors send a request immediately.

A node confirms a neighbors knowledge of a tag through an acknowledgment received in one of the ways mentioned before. Due to collisions, acknowledgments can be lost. Explicitly requests for acknowledgments are sent by the originator node, until all neighbors confirm their knowledge of the UID tag. In a manner similar to the retransmission of requests, the timeout interval before re-requesting an explicit ACK is set as an exponential back-off timer. By regulating the rate at which explicit acknowledgments are requested for, duplicate requests in the queue and redundant retransmissions can be reduced.

Node Failures do not affect the working of the protocol because data are always sender-advertised and retrieved by the receiver. But to maintain accurate neighbor lists at each node, it is necessary that neighbors which do not transmit any messages be timed out, so that explicit acknowledgments are not requested from them. Every time a new neighbor is detected, all the UID tags possessed by this node are marked as unacknowledged. The node then has to confirm knowledge of the tags with the newly added neighbor through exchange of content tables to ensure convergence. This suits incremental deployment of sensors in the field. This message exchange in-addition accommodates a mobile observer collecting information in the existing framework, since the mobile observer has to advertise all known tags, and can collect new information from the sensor node.

The same protocol can be extended to mobile or hybrid mobile scenarios (where selected set of nodes are stationary). The convergence of the protocol is not affected by the mobility of the nodes if each node is exposed to nodes having new data for a time enough to retrieve the available information. The only minor modification that is needed from the basic protocol is the necessity that Neighbor *HELLO* messages be broadcast at regular intervals, so that nodes can detect changes in their neighbor set and attempt to ensure convergence by broadcasting their content tables. The Hello message is a zero count content table.

4 Performance Analysis

The performance of SPROID and SPIN-RL (Reliable version for Single Channel broadcast) are compared on a realistic scenario for event-driven sensor networks.

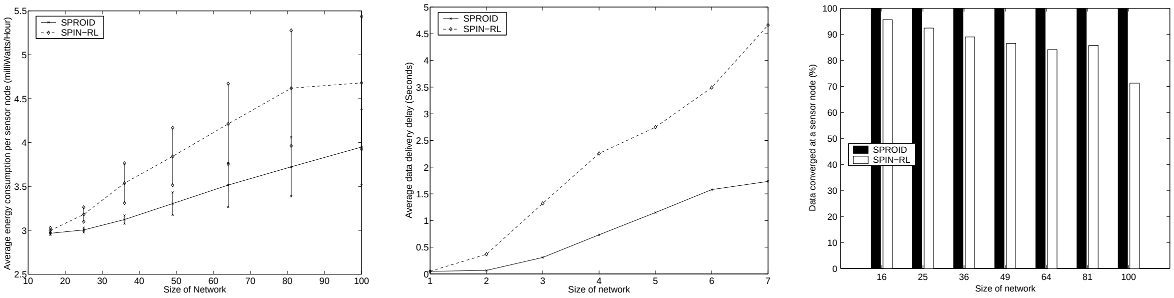
SPROID and SPIN-RL were implemented in Qualnet [10], a discrete event packet simulator. Suitable modifications were done in-order to simulate sensor networks. The MAC layer chosen for this simulation was 802.11 MAC and a physical layer bandwidth of 2 Mbps. The power consumption model was modified to reflect usage in sensor network radios, where listening and idle power consumptions are not identical. To get a realistic usage of power, the power consumption values were modified in accordance with [4] [7]. Idle time power consumption was 35 mW, transmit power consumption was 660 mW, receive power consumption was 395 mW. UID tags and data were 16 bytes and 500 bytes long respectively. The radio range was set to 10 m. Energy consumption due to radio state transition was not considered in these simulations. We use a realistic event-driven data generation model. An event happening in the vicinity of a set of sensor modes lasts for a finite time. We model this burst of data as 10 new UID tags generated by each sensor node, each being uniformly distributed in an one second interval. We present simulation results for data generation rates faster than 1 event/second on a fixed size network as well.

Experimental results obtained by simulating the protocols on a static grid and random connected topology are presented for different network sizes. The following aspects of the protocol performance were evaluated (a) average data delivery delay, (b) average energy consumption, and (c) percentage of data disseminated.

In addition, the above parameters are evaluated keeping the number of nodes in the network fixed and increasing the data generation rate for grid and random connected.

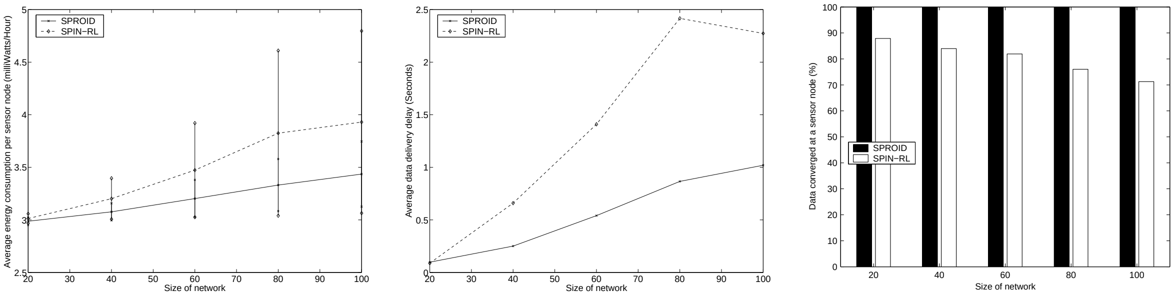
The grid networks were set to the following dimensions 4x4, 5x5, 6x6, 7x7, 8x8, 9x9 and 10x10. The mobility of the network was set to static. The results were averaged over 3 seeds. The random topologies were generated with static nodes being uniformly distributed to create a connected network. The size of the network and the terrain dimensions were modified to ensure a consistent node density. The results were averaged over 10 seeds for network sizes of 20, 40, 60, 80 and 100.

The performance of the protocols with respect to the rate of data generation was simulated by choosing a 7x7 node grid and a 50-node random connected topology. The sensors were made to generate 10 new events, with each event being uniformly distributed in intervals ranging from 250 milliseconds to 1500 milliseconds. The ability of the protocols to respond to an increased rate of data generation was the criteria for evaluation.



(a)Energy Consumption (b) Average data delivery delay (c) Data delivery

Figure 3. Grid Topology



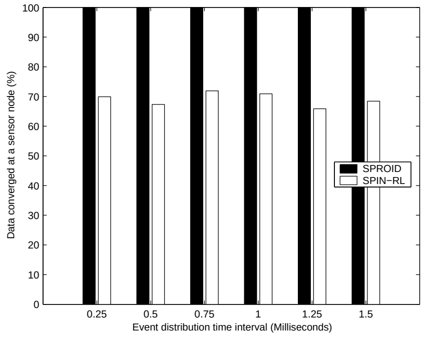
(a)Energy Consumption (b) Average data delivery delay (c) Data delivery

Figure 4. Random Topology

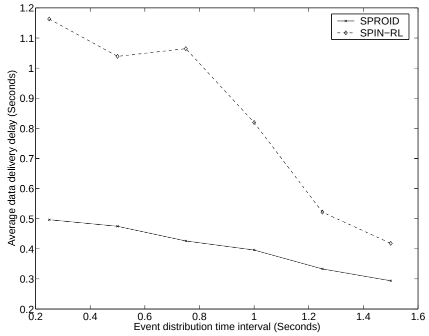
Figs. 3(b) and 4(b) show the average delay in delivering data for a UID tag to all the sensor nodes for the different networks. The delay is the time taken by a UID tag after being generated by a sensor node to reach all other nodes in the network. SPROID has a average delay lower than SPIN-RL, and scales well despite increasing network size, achieving data delivery at a faster rate. The average delay of data delivery when the rate of data generation is varied is shown in Figs. 6(b) and 5(b). The results indicate that when there is a increase in the data generation, both protocols incur more delay in distributing data. However, SPROID is able to achieve lower delay than SPIN-RL. Performance improvement for SPROID is due to the use of content tables which help to disseminate information quickly across multiple hops. The back-off timers minimize redundant transmissions and regulate retransmissions according to perceived contention for the medium.

Figs 3(c) and 4(c) show the percentage of average data converged at a node for the different scenarios. Figs. 5(a) and 6(a) show the data delivery percentage with different data generation rates. SPROID achieves 100% convergence in all cases whereas SPIN-RL does not. This is due to the problem of advertisements for UID tags getting lost in SPIN, whereas the presence of a explicit acknowledgment scheme in SPROID ensures complete convergence.

Figs. 4(a) and 3(a) show the results for the average en-

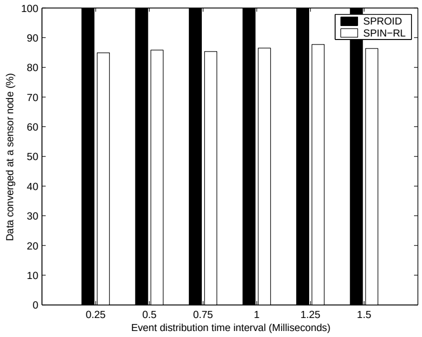


(a) Data delivered

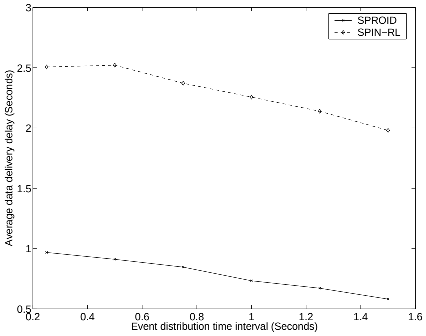


(b) Data delivery delay

Figure 5. Random Topology



(a) Data delivered



(b) Data delivery delay

Figure 6. Grid Topology

ergy consumption by a sensor node in the different scenarios. SPROID has lower energy requirements although it delivers more data. Energy efficiency results directly from minimizing retransmission of redundant data and keeping the probability of collisions to be low. The wider deviation of energy consumption amongst nodes in SPIN can result in nodes having different lifetimes and affect network connectivity.

5 Conclusion

We have presented a new protocol, SPROID, for reliable information dissemination to all nodes in a sensor network with an event-driven data delivery model. The protocol was designed taking into consideration the wireless lossy channel faced by sensor networks. This is the first data dissemination protocol for sensor networks which maintains reliability. SPROID has been compared with SPIN which is the other data dissemination protocol falling under the event-driven data delivery model. Simulation results under realistic event-driven scenarios show that SPROID scales with increasing number of events detected and increased rates of data generation while maintaining reliability, achieving faster dissemination and consuming energy efficiently.

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