Research Article

Reliable Latency-Aware Routing for Clustered WSNs

Ali Tufail

Graduate School of Information and Communication, Ajou University, Suwon 443-749, Republic of Korea

Correspondence should be addressed to Ali Tufail, ally.tufail@gmail.com

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1. Introduction

Wireless Sensor Networks (WSNs) have gained focus in last decade or so. The reason of this increased popularity is the support for wide array of crucial application including military, healthcare, industrial monitoring, target tracking, smart homes, and habitat monitoring [1, 2]. A WSN is typically composed of tens to thousands of resource-constrained sensor nodes. These sensor nodes are usually deployed to observe a target phenomenon and report it back to the sink. Besides other resource constraints these nodes have limited battery, signaling, and communication capacity. All these limitations make successful source to sink communication all the more exigent [3].

WSNs and its unique characteristics require special protocols to be developed which are different than those of the traditional wireless or ad hoc networks. Reliable source to sink communication is of the top concern in WSNs [4]. Reliable communication can be very crucial for applications like health monitoring where any failure in the communication can result in a big loss [5]. In a traditional wireless or wired network the communication and the source to the destination link are usually less prone to failure or interference. On the contrary, in WSNs the multihop communication is dependent on the intermediary nodes and any failure in the node or the link can result in failure of the communication. Apart from reliability, latency can be another important factor to be considered in WSNs. Lower source to sink latency can serve as the backbone of the crucial life saving applications.

This paper presents a reliable and latency aware-routing protocol. The proposed protocol works in the clustered WSN environment. Each cluster is managed and controlled by a resource-rich gateway node (GN). In order to have a reliable source to sink communication the proposed protocol makes use of the hotlines that exist between the GNs [6]. Although GN centric routing provides reliability, in certain cases it adds additional latency. This latency is more obvious in cases where the source and the sink lie around the border of the clusters. In order to make this protocol reliable and latency aware this paper presents a border node (BN) routing alternative. The BN routing will not only reduce the source to sink latency but would also increase the reliability by decreasing the number of wireless hops.

The rest of the paper is organized as follows. Section 2 describes related work. Section 3 discusses our network model and assumptions. Section 4 introduces the proposed reliable and low-latency routing protocol. Section 5 gives an overview of the simulation results. Section 6 summarizes key conclusions of this work.
2. Related Work

While reliability of homogeneous WSNs has been investigated in prior studies [7–10], reliability analysis of backbone approach in WSN is largely unexplored. In [8], authors formulate a WSN reliability measure that considers the aggregate flow of sensor data into a sink node. This measure is based on a given estimation of the data generation rate and the failure probability of each sensor. Common-cause failures (CCFs) have been discussed and identified as the cause of unreliability in WSN in [9, 10]. Authors in [9] consider the problem of modeling and evaluating the coverage-oriented domain of WSNs. In [11], authors discuss the latency issue in the issues of reliability together with the latency in the infrastructure communication reliability of WSN. In [7], the authors compute a measure for the expected and maximum message delay between data sources and data sinks in an operational distributed sensor network (DSN). Authors in [11] present a reliable routing protocol that forms the reliable routing path by utilizing network topology and routing information of the network. However, their protocol and analysis are application specific. Moreover, they have not provided any comparison with the existing reliability protocols.

We can find quite a few papers in the literature that deal with the issue of latency issue of WSNs but to the best of my knowledge this is the first paper that directly addresses the issues of reliability together with the latency in the domain of WSNs. In [12] authors discuss the latency issue in conjunction with the power-saving mechanism. Authors in [13] try to solve the data aggregation issue in WSNs by providing an energy-efficient protocol and claim that the protocol provides reduced latency.

In [14] we presented a Signature-Based Routing protocol (SBR). The purpose of that protocol was also to reduce the end-to-end latency. However, SBR is heavily dependent on the GN and puts much more computation and monitoring burden at the GN. Moreover, in SBR the source node first has to establish a path with the default GN irrespective of its position near the BN. It is only after the GN observes latency much higher than the average latency that the source node is suggested to form an alternative route via BN. This paper introduces BN advertisement messages and BN association mechanism. This new mechanism helps reduce end-to-end latency even further. There is no need to establish a path with the default GN first. Additionally, the extra computation and monitoring overhead has been taken off the GN.

3. Network Architecture

This paper considers a WSN with two-level heterogeneity. The first level has resource-constrained sensor nodes which are deployed densely on a two-dimensional grid. All of the first level nodes have the same resources. The second level has sensor gateway nodes (GNs) that operate as cluster heads to regulate the flow of traffic and to manage sensor motes deployed in the given geographical region. The GNs are not resource constrained and their density is many orders of magnitude lesser than the density of the sensor nodes. GNs are connected to each other in a bus topology via highly reliable links (hotlines), for example, Ethernet cables or point-to-point wireless links. The network topology is assumed to be fixed where both GNs and the sensor nodes are static. The communication from source to destination is multihop. Every node in the network is associated with at least one of the GNs. All the communication, by default, to and from the cluster is routed through the GN, with the exception of the border nodes (BNs). Each BN can connect two clusters by providing an alternative route for intercluster communication. As mentioned in Section 4, BNs would provide lesser latency and at the same time would provide more reliability by reducing the number of wireless hops from the source to the destination.

4. Overview of the Proposed Protocol

4.1. Clustering. Clustering is usually done to serve a particular objective like scalability, load balancing, latency, network management, and so forth [15, 16]. Our suggested approach is tailored to work on the clustered WSNs. Clusters are formed using the same technique as explained in [6]. Each cluster is managed by a gateway node (GN). GN acts as the cluster head for its cluster. All the nodes in a WSN must associate with any one of the GNs and set it as its default. It is worthwhile to mention here that nodes decide to join a particular GN depending upon the hop count. Hop count is calculated by every node after receiving the Router Advertisement (RA) message by the GN. In other words we can say that the closest of all the gateways will have a high probability to serve as the default GN for a particular node.

4.2. Border Nodes. Border nodes (BNs) are the nodes that lie in the overlapping region of clusters. These are shown in Figure 1. BNs are different than the other nodes in the cluster because (a) each BN receives the RA message from more than one GN [6] and (b) each BN can connect two clusters by providing an alternative route for intercluster communication. This paper explores the second characteristic of the BNs to provide lesser latency at the same time providing more reliability by reducing the number of wireless hops from the source to the destination.

There are two ways to communicate between a source and a destination. The default is the source-GN-GN-destination route. The other possible route is source-BN-destination. Later alternative route is expected to be suitable only for the first hop nodes of the BNs; otherwise it might yield more latency and less reliability. The route options are shown in Figure 3. On the other hand Figure 2 highlights the border nodes and its first hop neighbors on both sides.

4.3. Border Node Association. In order to have a communication using BNs, there must be some association mechanism that binds the first hop neighbors of the BNs to the BNs. This paper defines BN association mechanism that is similar to the GN association mechanism [6] except (a) BN association mechanism which is just targeted to the first hop neighbors.
and other with the next hop BN. For these kinds of nodes the communication from source to the destination can go via either GN or BN. Here it should be clear that BNs are also associated with at least one of the GNs. Depending upon the destination BNs can communicate either with the help of the GN or directly with the destination.

4.4. End-to-End Communication. If a source has to communicate with a destination, by default, it will discover the route towards the GN. This will not be true for the first hop neighbors of the BNs. For these nodes, BNs are first consulted. If the destination is one hop away from the BN it will tell the source to use BN as its default route, otherwise BN will reply in negative and the source has to use GN route to reach the destination. If the BN route is being used it means the source and destination are just two hops away. If we compare this route with the default GN route, we can see that in this case BN route is providing less latency and more reliability. Reliability is increased because end-to-end number of wireless hops is reduced.

Algorithm 1 explains how a source node tries to find out the route to the destination node.

5. Simulation and Results

This section discusses the simulations and their results. Table 1 explains simulation setup and the environment that has been utilized to conduct the simulations.

The simulations have been conducted by having the same network topology as defined in Section 3. All the traffic goes to the default GN except for the first hop neighbor of the BNs. The first hop neighbor of the BN first asks the BN about the destination if BN has the destination in its reach (within its first hop) then the route is established using BN; otherwise default GN route is established. All the GNs are connected via Ethernet cable. Multiple sources send data to the sink to emulate bursty traffic.
Legends
BN: Border Node, GN: Gateway Node, A: Source Node, B: Destination Node

(1) Start Communication—find a path from A to B
   (2) If A is first hop neighbor of the BN
       Find B
   (3) If B is first hop neighbor of the BN
   (4) Establish a path from A to B using BN
   (5) Else reach the default gateway
   (6) Establish a path from A to B using A’s and B’s default GNs
   (8) Else
   (9) Find B
   (10) Establish a path using default GN

Algorithm 1: Algorithm to find a path from the source to the destination.

Table 1: Simulation environment.

| Simulation environment | Qualnet 4.5 |
|------------------------|-------------|
| Routing protocol       | AODV        |
| Intergateway routing   | OSPF        |
| Intracluster communication | Wireless (802.15.4) |
| Intercluster communication | Wired (Ethernet) |
| Number of nodes        | 100         |
| Total terrain area     | 1500 m × 1500 m |
| Simulation time        | 4200 seconds |
| Total runs             | 30          |

For simplification and comparison purpose in this section the suggested scheme is called as Border Node assisted Routing (BNR). BNR is compared with the all wireless routing, hotline-assisted routing [6], and signature-based routing (SBR) [14]. For all wireless routing same network topology and node deployment have been kept. However, there are no GNs or Ethernet connections. For hotline-assisted routing GNs are deployed along with their Ethernet connections. For SBR latency-aware routing is utilized along with the hotline-assisted routing. Please note that the routing used in BNR is also hotline assisted but there is a difference in finding and establishing the source to destination route.

This section defines reliability as the percentage of total messages received successfully by the destination. Latency is defined as the time taken by a packet to reach from the source to the destination/sink. For better comparison it also includes time consumed to establish or to change/reestablish (in case of SBR) the route from source to destination.

Figure 4 compares all the protocols in terms of average end-to-end latency against node IDs. Please note that the node IDs are the same as in our experiment, only the nodes of one cluster are shown here. In Figure 4 nodes 11, 21, and 35 are the first hop neighbors of the BNs. We can see that all wireless routing is giving highest average latency for all the nodes except for the nodes 11, 21, and 35. The reason for this high latency for all the other nodes is that the traditional way of routing just includes wireless hops. Each wireless hop increases a certain amount of latency. However, nodes 11, 21, and 35 happen to have their destination quite close by, therefore they provide less latency as compared to the hotline approach. On the contrary, hotline-assisted routing is better than the traditional all wireless routing for most of the cases as it provides high-speed alternative to the wireless hops and reduces the total number of end-to-end hops. SBR and BNR both perform better than the basic hotline approach in cases where the source node is the first hop neighbor of the BNs; otherwise the performance is almost similar to the basic hotline approach. BNR outperforms SBR because the path establishment is simpler in case of BNR and path re-establishment phase has been completely removed from BNR which decrease the latency even further.

Figure 5 compares the protocols in changing network density. The figure summarizes the average of all the communication that took place during all the simulation runs for each protocol. We can see that all the three protocols are better than the traditional wireless routing. However, they are close to each other in terms of performance. BNR is slightly better than hotline-assisted routing and SBR due to the already explained fact that it considers an alternative routing path for the nodes which are first hop neighbors of the BNs. Although SBR also considers alternative routing path, the process to find that path is complicated and takes more time as compared to BNR.
introduces alternative path from the source to the destination by utilizing the border nodes (BNs). BNs also take the computation and monitoring overhead off by serving as the alternative forwarder or communicator between two clusters. The simulation results also prove that the suggested routing approach outperforms the previously suggested protocols by decreasing the latency and increasing the packet success ratio.

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