A WSN/MANET Hybrid Protocol for Routing Data in Heterogeneous Wireless Sensor Networks

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Abstract—In this study we develop a hybrid (dual-strategy) routing protocol for wireless sensor networks. This protocol can be used for two purposes at the same time. First, the protocol is responsible for routing data within sensor networks. These networks are composed of nodes with different capabilities and resources. The routing in this case is data-oriented. That is, it searches for nodes that can provide data with certain attributes rather than nodes with certain addresses. Second, it is used to route data between the capable nodes that are members of the sensor network in an address-oriented fashion. In this latter case, network sensor nodes are not involved in the communications or data routing between the capable nodes, which results in saving the energy and computing resources of these sensor nodes.

Keywords—Wireless Sensor Networks; MANET; Data-centric routing; Address-centric routing

I. INTRODUCTION

Wireless sensor networks (WSN) have many applications in which data about some sensed phenomena is collected. This data is then acted on and/or processed in order to serve the purpose for which the network was created. In many wireless sensor network applications, network nodes differ from each other in the capabilities and function. In general, a sensor network is composed of small static sensor devices of low computing power and resources and some higher capability devices, which can be either mobile or static. The main function of the small sensing devices is to sense one or more phenomena and transmit sensed information to specified network destinations. The higher capability devices are usually tasked with aggregating this information, validating it and making use of it based on network settings and function. Networks that exemplify the WSN heterogeneous structure can be found in many applications e.g. [4],[5].

We illustrate the use of heterogeneous networks in the following example. In the event of a natural disaster, a network of wireless sensor devices can be deployed in the affected area. These devices are required to sense one or more aspects of the surrounding environment such as temperature, gas emissions, human voices, etc. Emergency vehicles then roam around and subscribe to the network in order to get different kinds of information from the deployed sensors in order to guide the search and rescue operation. In this example, we see obvious differences in the capabilities between network nodes. For instance, some of these nodes are small sensor devices with very limited communications, storage, computation and energy resources. They are also mostly static. Other network nodes, such as the ones mounted on the emergency vehicles could be mobile and enjoy a much larger pool of resources relative to the tiny sensor devices.

This example shows that there are two types of communications that can be expected within this kind of networks. The first type of communications involves searching for and transmitting information that is collected by sensor nodes. This type is called "data-oriented" communications because it is centered around data in the sense that the search and transmission is based on specific data attributes. Data-oriented communications involve one or more sensor and capable nodes that are members of the network in question. The second type of communications is done between network capable nodes only. This is done for coordination and cooperation purposes. Since, usually, these capable nodes (such as ones mounted on emergency vehicles or personnel) are aware of the identity of each other; they communicate together using node addresses. We call this type of communications address-oriented communications. This network structure necessitates performing data routing using two routing strategies: one handles locating data, while the other handles locating nodes with specific addresses. Therefore, a strong case exists for designing a robust dual-strategy routing protocol that can be used for routing data in a network with these characteristics while accommodating the capabilities and needs of the different device types. It can locate and route data based on certain data attributes when sensor nodes are involved, while it is capable of locating nodes with specific addresses and routing data to them when only capable nodes are involved in the operation. Therefore, this protocol eliminates the need to use several networks which have some common nodes; where each of these networks is being used for a certain purpose or function. This in turn

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eliminates complex configurations and allows the use of simpler data sharing strategies.

The rest of this paper is organized as follows. In Section II, we discuss our protocol design approach. In Section III, we give a detailed description of the proposed protocol. In Section IV, we present the results of the protocol evaluation experiments. In Section V, we conclude the study.

II. PROTOCOL DESIGN APPROACH

In a previous study [3], we demonstrated that MANET protocols offer performance and robustness that can be relied on in wireless sensor applications especially mission critical ones. In fact, the performance of some MANET protocols has shown to be superior to some major protocols that have been designed specifically for wireless sensor networks. MANET protocols, however, lack some of the important features that are necessary for many of the sensor network applications such as the data-oriented operation. Our goal in this study is to build on the capabilities of this class of protocols, adapt them to the additional needs of wireless sensor networks and extend their abilities to make them feasible for a MANET/WSN hybrid operation without the need of some network nodes to use several protocols for this purpose. This way, the protocol can be used for both address-oriented as well as data-oriented operations simultaneously. In short, we aim at creating an end-to-end protocol that can be used to route data within both the MANET and WSN networks that share some nodes. In this network arrangement, sensor nodes, that are generally low capability devices, collect required information from the surrounding environment. We will refer to this category of nodes as source nodes throughout this study. These nodes then send this information to sink nodes, which are nodes that generally possess high computational, communication and energy capabilities. Sink nodes, which may be mounted on rescue vehicles or personnel, perform tasks such as data aggregation or processing. These sink nodes can also act as gateways between the WSN and the external world such as the internet. The source nodes together with the sink nodes form a WSN while the sink nodes alone form a MANET in which they cooperate in processing data, carrying out a certain mission, or transfer the data to external parties or networks. We have shown in [3] that protocols of the reactive category of MANET e.g. AODV [2] offer a robust performance and therefore we use AODV as our starting point in the development of our proposed solution. It should be noted that while we are not discussing addressing techniques in this study, there exist some addressing techniques (e.g. [6]) that are suitable for use with our protocol to achieve the sought end-to-end operation.

III. DETAILED PROTOCOL DESIGN

The main idea in the design of this protocol is that all network nodes should cooperate when it comes to transferring sensed data from its sources to the processing centers or data sinks. However, when communication is required between the capable devices within the network, the low capability devices should be excluded in order to preserve their limited resources for monitoring and reporting certain phenomena. This idea is illustrated by the high level diagram of Figure 1. From this figure, we see that at the network initialization and neighbor discovery stage, all network nodes are treated the same and no distinction is made between nodes based on their capabilities. This is also the case when a new node joins the network.

A. Address-oriented routing mode of operation

Address-oriented routing follows the original AODV algorithm [2] closely. This is due to the fact that it will only be used by capable nodes which know each other’s address and need to communicate with each other using specific
node identifiers. This type of communications needs the full capabilities that are offered by the original AODV technique and at the same time the involved nodes can afford the kind of communications cost that is involved. We will, however, add some optimizations that will ensure a prolonged operation in case the nodes in question are of the static type that can be planted remotely and their batteries (or source of energy) are not easily replaceable.

The main modification is in the route expiry policy. Instead of having the routes expire after a fixed pre-configured amount of time, the route is set to never expire by default. This changes only if the route reply (RREP) message shows that at least one node on the route is mobile or its remaining energy reserve is below a certain predetermined threshold. The mobility condition of the node can be determined by the application and passed on to the routing layer. Route expiry time can be determined based on the mobility level and the level of energy. Alternatively, and to simplify the algorithm, a fixed expiry value can be assigned to this particular route if node mobility or low energy level is detected. The address-oriented routing operation is illustrated in Figure 2.

B. Data-oriented routing mode of operation

In this mode of routing operation, the protocol follows a pull model. That is, a sink node triggers the search operation for data of certain attributes only when it needs this data. Some other techniques use a push model, which enables the sensors within the network to advertise the fact that they have data of specific attributes so that sinks can locate this data rather fast when they need it. The advantage of using a pull model by sink nodes as opposed to a push model by sensor nodes is the considerable reduction in traffic since data would be communicated only on-demand. However, the pull model may imply extra delays as data will have to be searched for and located when it is needed.

1) Data query request: In the data-oriented operation of this protocol, sinks request data based on certain attributes. They also specify the schedule and timing of transmitting this data. We will denote this data request as Query Request, or simply QREQ, throughout this study. There are several possible timing types of a QREQ. One type is "immediate" QREQ. This means that the information is required if exists immediately. If not available immediately at the receiving sensor nodes, the QREQ is discarded. This can be the case when there is a worry of serious temperature increase or gas emission in a certain area, and in this case the query specifies the area of interest for verification. The second timing type of a QREQ is the one that is bounded by a certain period of time. This means that nodes that fulfill some conditions of the QREQ but do not have immediate data can always keep the QREQ that they receive for the specified period of time as indicated in the QREQ packet and then discard it if data is not sensed within this period. The third timing type is the time unbounded QREQ. This is the case when an ongoing monitoring of some phenomenon is required. The QREQ in this case is associated with the intervals at which the reporting is needed.

Figure 2: Address-oriented routing operation

2) Data query reply: Once a node that is a source of the required data, or a node that knows a source of this data, receives a QREQ, it issues a query reply packet, QREP, and sends it back in the direction of the requesting sink node. The route that has to be taken by the QREP packet is included at each node, on a hop-per-hop basis (given by the next hop identifier), in its Data Query table that we will describe later in this section. The node that originated the QREQ packet checks to see if the TTL value in the QREQ packet that it had received has expired. If it did, it simply discards the packet. Otherwise, it forwards it to its neighbors in case there are other source nodes that meet the required condition.

After the sink node that requested this data receives a QREP packet from a source that meets its conditions, it adds this info to its Query Data table and sends that source an ACK packet that tells it that it can start data transfer operation (according to the query preset conditions) using this specific route. If the source node does not receive an ACK packet after a certain timeout period, it resends the QREP to the sink on the assumption that its previous QREP was lost.

Figure 3 demonstrates the data-oriented operation of the proposed protocol.

C. Route Maintenance

In case of address-oriented routing, route maintenance is done as per the AODV routing protocol procedures [2].

In data-oriented routing, a route between a source and a sink may get broken if a mobile sink node on this route moves away or if a low capability device on the route depletes its energy. In this case, a query route error is sent from the node at which the route breakage is discovered to the source node. Then, the source node starts buffering packets destined to this sink, if any, and issues a query route fix (QFix) packet to search for a new route to the sink in question. Once the sink receives a QFix packet, it responds back with an ACK packet similar to the one that it sends in
response to a QREP packet in the initial route establishment phase. Once the source receives this ACK packet, it resumes data transmission to this sink.

![Figure 3: Data-oriented routing operation](image)

D. Protocol specific packets

Since this protocol supports two modes of routing operation, namely, address-oriented routing and data-oriented routing, it uses protocol-specific packets that pertain to each mode separately. While the protocol uses the regular AODV protocol packets [2] for the address-oriented operation, we have developed protocol-specific packets for the data-oriented operation as follows:

- **Query Request (QREQ):** A sink node sends this packet when it is looking for data related to some phenomenon. It includes attributes of the required data such as: query type (kind of data that is required), threshold (required data threshold), timing (immediate/within a time period), condition (a qualifying condition for locating data), period (required data sending interval) and data rate.

- **Query Reply (QREP):** It is the response to a QREQ when data is located. It mainly includes: type, threshold, value (of the required data), condition, event time, route expiry bit (as explained above).

- **Query Reply ACK (QACK):** Sent by the sink when it receives a QREP or QFix from a source node. It triggers the source to (re)start sending data to the sink.

- **Query Reply Cancel (QCancel):** If a sink node wants the traffic from a source node to stop before the end of the agreed on period, it sends a cancellation packet asking it to cease its transmission. This may happen, for example, when the sink discovers a better route to the source than the current one, so it asks it to stop the traffic on this route. Later, it may send it a QACK packet using the newly discovered route.

- **Query Route Error (QError):** Sent to a source by a node on a route between this source and a sink when its link layer detects a route breakage to the sink.

- **Query Route Repair (QFix):** Issued by a source to look for a new route to a sink upon route breakage.

E. Data query table

As far as address-oriented routing is concerned, the regular AODV routing table is used taking into consideration the route expiry policy that we discussed earlier. On the other hand, when data-oriented communications are concerned, a new table, the "query data table" is used where information on how to route data from a source to a sink is stored on relevant network nodes. In this table, information about the attributes of the data of interest such as data type, threshold, condition, sink address, source address, next hop, hop count, route expiry etc, is stored.

IV. PROTOCOL EVALUATION

In order to evaluate the proposed protocol, we implemented it and conducted extensive simulation experiments using the network simulator, ns2 [7]. The purpose of our evaluation is to test the hybrid WSN/MANET functionality of the protocol and examine its performance in the two routing modes. We aim at ensuring that the hybrid feature of the protocol was not established at the expense of either its address-oriented or data-oriented routing performance. For this purpose, we compare the address-oriented routing performance of the protocol to the routing performance of the AODV protocol [2]. We also compare the data-oriented routing performance of the proposed protocol to that of the directed diffusion protocol [1], which is a pioneering data-oriented routing algorithm.

In our experiments, we use four metrics: two for the data delivery performance and two for the sensor nodes' energy performance. For the data delivery performance, we use the average packet delivery ratio and the average packet delivery latency. For the energy performance, we use average energy consumption of sensor nodes and energy fairness, measured by the standard deviation of remaining sensor node energies.

We conducted several experiments where we tested the hybrid operation of the protocol, checked the performance with changing the number of sources and sinks, with sink mobility and with varying the data rate of the sources. Due to the limited space, we only show the results of some of these experiments.

The simulation area is 1000×1000 m². Default simulation parameters are as follows. Total number of network nodes is 100. Number of sinks is 4 and that of sources is 4. The data rate of source nodes is 1 packet/sec. Data packet size is 64 bytes. Initial sensor energy is 200 J and that of sink nodes is unlimited. The Rx, Tx and idle power consumption values for sensor nodes are 0.395, 0.66
and 0.035 Watt, respectively. Experiment simulation time is 600 seconds.

Each sink node is assumed interested in the data detected by each source node in the network i.e., a source-sink connection is to be established for all source-sink pairs within the network. We run each experiment ten times and the result of an experiment is the average of all ten runs.

1) Hybrid operation of the protocol: We change the number of capable nodes in this experiment to be 30 through 50 nodes. These capable nodes form the MANET network (address-oriented routing) in which there are 8 traffic connections each with data rate of 3 packets/sec. For the data-oriented operation, the parameters are as stated above. We run experiments to compare the performance of AODV and the address-oriented mode of the proposed protocol. We also test the data-oriented operation of the proposed protocol at the same time. Figure 4 shows that the packet delivery performance of the hybrid protocol for the address-oriented operation is almost identical to the performance of AODV. This is despite the fact that there is also the additional data-oriented data traffic when testing the hybrid protocol. This traffic was not included in the network when testing AODV. We also see from the figure that the data-oriented packet delivery ratio of the hybrid protocol is almost 100% for all values of the number of capable nodes within the network. This ratio is not affected by the traffic that is occuring in the MANET network simply because sensor nodes are not involved in the MANET data routing at all. From Figure 5, we also see that the latencies in both procols are quite comparable. It should be mentioned that the latency in case of the address-oriented routing of the proposed protocol is a bit higher than AODV due to the fact that the capable nodes are also involved in the data-oriented data traffic in case of the hybrid protocol unlike the AODV experiments where there is no data-oriented traffic in the network.

2) Operation with sink mobility: In this experiment, we demonstrate the data-oriented routing performance of the proposed protocol when the sinks are mobile. We compare this performance to that of the directed diffusion algorithm. We vary the level of mobility of sinks by changing the pause time to take the values 100 through 600 seconds. We see from figures 6 and 7 that the route maintenance capabilities of the proposed protocol enable it to recover from route breakages that results from sink mobility faster than the directed diffusion algorithm. The packet delivery ratio of the proposed protocol is almost unaffacted by the mobility and packet delivery latency remains much lower than that of directed diffusion regardless of the mobility level. As for the energy performance, we see from figures 8 and 9 that energy consumption is consistent in the proposed protocol regardless of mobility and remains significantly lower than directed diffusion. This is also the case as far as energy fairness between sensor nodes is concerned.

3) Operation with varying number of sources: In this experiment we test the data-oriented routing performance of the proposed protocol as compared to directed diffusion with the increase of the number of data sources. Figure 10 shows the packet delivery performance of our protocol as compared to that of directed diffusion. We see from this figure that our protocol performs consistently better than the directed diffusion algorithm regardless of the number of sources at this data rate. In Figure 11, we see that the hybrid routing algorithm results in negligible packet delivery latency despite the pull model that it uses. The directed diffusion algorithm, on the other hand, results in a packet delivery latency that increases with the increase of the number of sources. Figure 12 shows the energy consumption performance of the two algorithms. In this figure, we see that the energy consumption trend increases in a much steeper fashion in directed diffusion as compared to the hybrid routing algorithm which shows moderate energy consumption in all cases. Energy fairness seems to be far higher in our algorithm. This is evident in its lower standard deviation trend as compared to that of directed diffusion. This can be seen in Figure 13.

V. CONCLUSIONS

In this paper, we introduced a new routing technique that enables hybrid routing operation in wireless sensor networks. It is designed to allow address-oriented routing for capable nodes within the network. It also allows data-oriented routing, which is crucial for the operation in many wireless sensor network applications. We discussed the design goals of the protocol as well as the details of its architecture and features. We presented the results of the test experiments that we conducted to evaluate the performance of our protocol. Our results show that the address-oriented operation performance of our protocol is almost similar to that of AODV. They also show that the data-oriented operation performance of the new technique performs clearly better than purely data-oriented routing protocol, directed diffusion.

REFERENCES


Figure 4: Packet delivery performance in hybrid operation vs AODV

Figure 5: Packet latency in the hybrid routing algorithm vs AODV

Figure 6: Effect of sink mobility on packet delivery ratio

Figure 7: Effect of sink mobility on packet delivery latency

Figure 8: Effect of sink mobility on energy consumption

Figure 9: Effect of sink mobility on energy fairness

Figure 10: Effect of number of sources on packet delivery ratio

Figure 11: Effect of number of sources on packet delivery latency

Figure 12: Effect of number of sources on energy consumption

Figure 13: Effect of number of sources on energy fairness