Reliable Real-Time Data Acquisition for Rapidly Deployable Mission-Critical Wireless Sensor Networks

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***Abstract*—The nature of military operations introduces additional requirements on sensor and ad-hoc networks such as reliability and operating in real-time. Although there has been many techniques providing reliability and real-time data communication in the literature, their implementations challenge with resource limitations peculiar to Wireless Sensor Networks (WSN). Real-time data demand and reliability challenge with the objective of minimization of energy consumption. Moreover, most of these techniques require topological information of the deployed network which introduces communications and processing overhead. In this paper, we present an energy-efficient and reliable data acquisition approach for time-critical and real-time traffic in WSN applications. Real-time data is carried over multiple paths to provide reliability in communications. The proposed approach provides the ability to route data without topology information. Moreover no complex computations are required. The performance evaluation shows that the proposed technique fulfils the requirements of tactical communications of instantly deployable sensor networks in a hostile environment. Although the proposed method is developed for instantly deployable sensor and ad hoc networks such as those deployed in emergency cases, in hostile environment and, in dangerous environments, it can also be applicable for preconfigured networks.**

Keywords-component; mission-critical networks; real-time; energy-efficiency; reliability; rapid deployment; mobility.

I. INTRODUCTION

Wireless Sensor Networks (WSN) is progressively utilized in homeland security, disaster recovery, etc., and are planned to be used intensively in near future. Networks composed of video and audio sensors can be used to provide monitoring and surveillance systems or can be used to enhance the existing ones. Some critical areas for homeland security, such as borders, gulfs, strait entrances and port approach waters, are subject to enemy infiltration in crisis and wartime. We believe that using an instantly deployable network composed of sensor nodes in these operation areas would be a good solution for increasing the probability of detecting a penetration in a cost effective and efficient way than the conventional ones.

Moreover, the nature of military operations introduces additional requirements on sensor and ad-hoc networks such as reliability and operating in real-time. Acquired raw data in a detection system is required to be conveyed to a processing and evaluation center in a short time to preserve validity and value of data as well as to provide short response time. Note that the loss of data is unacceptable. Resource limitations of sensor devices and the properties of wireless transmission media challenge with these objectives. Limited battery life of the nodes requires efficient energy consumption techniques which challenge with real-time and reliability requirements. Moreover, mobility of nodes degrades the performance of the system, making the problem more challenging and impractical.

Reliability can be provided by enabling redundancy in transmission, which can be done by constructing several paths from source to destination and traversing the same data packet through each of these paths [1]. It's also known that multiple path usage also aids load balancing in the network as well as reduces the effects of congestion that is highly probable to occur in multi-media traffic and bursty traffic. On congested nodes, UDP packets are dropped which causes the performance degrade in communications which is more critical issue in real-time systems. In case of packet loss, multiple path usage has already provided the mean for data flow over other remaining paths those circumventing the congested area. By this way, desired data rate at the destination can be satisfied.

Mobility of network elements introduces additional overhead, increases complexity and makes the conventional routing algorithms fail. Therefore, novel and special algorithms are required for mobile environments.

We propose a new approach based on the Stateless Weighted Routing (SWR) [2] for instantly deployed wireless sensor networks. The SWR spontaneously makes data flow per se over multiple paths from data sources to the sink to provide reliability. Real-time communication support in SWR is provided by using a priority scheme. Multiple path construction does not require any algorithmic modification in the SWR algorithm. The SWR adapts itself dynamically according to the current conditions and parameters without extraneous modification. Moreover, proposed approach reduces the energy consumption due to geographical routing applied in the SWR. To the best of our knowledge, the proposed approach is the first one that uses multiple paths to provide reliability while considering minimization of energy consumption.

In the next section, related work is given. Reliability methods for real-time traffic are described in Section 3. Performance evaluations are given in Section 4. In the final section the paper is concluded.

II. MOTIVATION

In monitoring and tracking military applications for homeland security and in other time-critical applications for public security, two co-existed aspects are very important and unaffordable about the arrival of data at the destination to capture the current view at the moment: 1. in-time arrival of data still keeping its valid information. 2. arrival of data in-time and continuously without damage or corruption. These two aspects integrate with each other and absence of one neutralizes the favor of the other one. Arrival of data in-time can be provided by reducing the delay to minimum during the transportation of the data to the destination. Long-range single-hop transmissions between the source and destination provide the minimum delay. However, resource limitations on power, frequency and bandwidth enforce to use multi-hop communications. On the other hand, multi-hopping increases the end-to-end delay and introduces reliability problem due to probability of fail at each transmission.

There are many routing approaches to provide either or both of the objectives of reducing the end-to-end delay and providing the reliability. However, most of them challenge with other aspects such as energy-efficiency, long-lifetime and low-cost expect of the system. Energy aware protocols in the literature generally use multi-hop paths to use energy more efficiently. However, increase in number of hops between the source and the destination nodes bears some issues that must be considered [3, 4]. First of all, nodes close to the sink deplete their energies quickly; leaving the sink unreachable and forcing the system into off-state [5]. Secondly, increase in the hop-number cause more nodes to buffer the packet on-the-route, causing a processing overhead and delay at in-between nodes. Processing overhead and buffer fill-up may cause packets to be dropped. On the other hand, delay at nodes may prevent to fulfill the real-time requirements of the system [3]. As the network size grows, the length of the constructed paths will increase, causing the problem described above more challenging. New routing techniques which provide reliability and real-time response to sensor readings in energy efficient way are always required in WSN.

III. RELIABLE REAL-TIME DATA ACQUSITION

In our approach, we use the SWR which is a stateless and reactive routing protocol that utilizes the geographic location information for routing. Routing tables and local/global topology information are not kept at nodes. Routes are constructed on-demand. Nodes do not need to know the identities of their neighbors even. Eliminating the need of the neighborhood information on route construction avoids the beacon messaging and advertising. Routing is achieved with aid of weight values of nodes which is derived from the geographical positions and some QoS parameters (1).

$$w_i = location_i + parameters_i + parameters_{network} \quad \textbf{(1)}$$

Each node derives its own weight value (w_i) dynamically from its current position and some QoS parameters such energy left at the node. These parameters may belong to either the node itself ($parameters_i$), the network's current situation, the current mission, the goal of the network ($parameters_{network}$) or a combination of these two. If none of these parameters is included in the weight function, the weight value indicates the square of the Euclidian distance to the sink node (2). Nodes away from the sink node usually have greater weight values with respect to closer ones, as the sink has a weight value *0*. The use of weight metric makes the routing process simple and minimizes delay, energy consumption, and processing requirements at nodes in routing decision phase.

$$w_i(x_i, y_i) = x_i^{\,2} + y_i^{\,2} \quad \textbf{(2)}$$

The SWR uses the packet header shown in Fig. 1. The source node inserts its weight value into the packet and broadcasts. When a node receives a packet, it

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compares its own weight value with the weight value in the packet. If its weight value is between the transmitting node's weight value and the destination's weight value (that is *0* for sink), it rebroadcasts the packet, otherwise drops the packet. Since this approach constructs multiple paths, in order to limit the number of transmissions and the number of multiple paths, a threshold value in metric of weight is used. The threshold value is included in the packet header as shown in Fig. 2.

A. Quality of Service Parameters

To enhance performance metrics, one byte long QoS Parameters field is included in the packet header. Except for the threshold field, which is required for the SWR, QoS fields are not mandatory considering non real-time communication. Though the SWR protocol provides the minimum delay between the source and the sink node, and reduces the energy consumption considerably without integrating such a QoS field, some QoS parameter fields are added to support real-time data transmission. Details of QoS Parameters field are shown in Fig. 2.

Threshold field is used to reduce energy consumption by regulating the number of transmitting nodes; to adjust the number of possible multiple paths; and to recover from voids. The use of threshold field is explained in details in [2]. Priority field is introduced to provide priority in transmission. It is assumed that three levels of priority would be sufficient to support real-time traffic. These levels that are the priority values and their meanings are given in Table I. Silence field is used to suppress the existing communication and to provide a silent state for urgent data transmission in emergency conditions in addition to security, energy saving, reconfiguration of the network and other possible on demand needs. Silence field could be considered as a boolean value. Although not utilized yet, the Packet Type field is used to differentiate between the packet types, which may imply different values of priorities. The values and their meanings are given in Table II.

B. Data Packet Transmissions

If a node has a data to send to the sink, it inserts its identification number, current packet sequence number, and the intended destination's identification number into the appropriate fields. Also, it inserts its identification number and the current weight value into the Sender ID and Sender Weight fields, respectively. In QoS Parameters field, Threshold field is set to system-wide default value which is actually 50%, but can be changed according to the network dynamics. Priority field is set to Normal, and the Silence field is set to Normal (0). The Packet Type field is set as data packet. Then the node broadcasts the packet. Actually, the packet is passed to the MAC layer to be sent to the addressed nodes. Aforementioned values used in QoS field are set according to the normal conditions. For other conditions, e.g. on emergency conditions, appropriate values should be used.

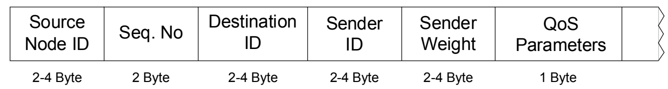

Figure 1. Simple packet header and its QoS fields

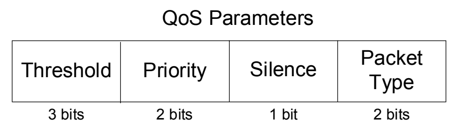

Figure 2. QoS fields of the packet header

TABLE I. VALUES AND CORRESPONDING MEANINGS OF THE PRIORITY FIELD IN THE QOS PARAMETERS FIELD

Value	In binary	Meaning
0	00	Forced Data
1	01	Urgent Data
2	10	*Reserved*
3	11	Normal

TABLE II. VALUES AND CORRESPONDING MEANINGS OF THE PACKET TYPE FIELD IN THE QOS PARAMETERS FIELD

Value	In binary	Meaning
0	00	Data packet
1	01	Ack.
2	10	Interest Packet
3	11	Position Packet

IV. SIMULATIONS AND RESULTS

The application scenario for simulation is realized considering a Sea Surface and Underwater Surveillance and Defense System. The system assumed to be deployed over the Littoral Penetration Area (LPA) such as gulfs, strait entrances and port approach waters. The system is composed of two types of components; low cost, resource-poor sensor nodes to sense, detect and monitor the environment and resource-rich actuator nodes to perform appropriate reactions to the events. Each sensor node which is attached to a buoy to float freely over the sea without a propulsion mechanism is equipped with a group of sensors such as magnetic, acoustic and thermal. Sensor nodes are also equipped with a servo-motor to plunge the sensors into water providing a desired depth [6]. The changes in the noise, temperature and magnetic levels are acquired by

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sensors and send to actuator nodes in order to track any possible act of penetration. The actuator nodes classify and identify the penetrating object and perform the required reaction.

A. Mobility Pattern

Mobility patterns in the literature [7] are not appropriate to represent the behavior and movement of objects on sea surface. For example the approach is presented in [8] is too simple and ignores the actual indeterminist mobility of objects in sea surface. Therefore, a novel mobility model for the floating objects which are subject to wind, wave, and current is proposed. Assumptions and approaches are made to reflect the intrinsic facts and behavior of objects on sea surface. Nodes' individual movement is based on the Random Walk Mobility Pattern where the group mobility, is based on the Reference Point Group Mobility Model. Two separate mobility scenarios are designed to represent both the sea surface close to hyaline and the sea surface having a strong current. Speed and direction of the nodes and group are determined to simulate the movement of sensor nodes over the sea surface. In the first mobility scenario, nodes move with a low speed (because of the very low impact of current and wind), that varies randomly between 0-5 meters per minute. Group mobility is 2 meters per minute towards east with in a sector of ±15 degree, According to the given set of parameters, a node moves on the sea surface with a speed of 0-0.13 knots (miles per hour). In the second scenario, highly mobile nodes (because of the very high impact of current and wind), are considered. The speed of nodes varies randomly between 0-60 meters per minute. Group mobility is 30 meters per minute towards east within a sector of ±90 degree. Direction of the nodes varies randomly within the 180 degree sector centered with the group's general direction. According to the given set of parameters, a node moves on the sea surface with a speed of 0-2 knots (miles per hour). The sink node always moves to the center of the group where the optimal place is for both scenarios.

B. Scenarios

In simulations, protocols are tested against two different scenarios. In both of the scenarios, sensor nodes are randomly distributed in a well-defined topology. In the first scenario, the effects of the routing algorithm to the energy consumption and lifetime are observed. Randomly generated, UDP based Constant Bit Rate (CBR) traffic is used for evaluations. Nodes randomly generate 128 Byte payload packets with a probability of 0.05 packet/min. Packet generation frequency is increased to 1 packet/sec to observe the effects of load to the energy consumption. To provide the double range property, nodes have a sensing range (R_s) 50 meters and a transmission range (R_c) 100 meters ($R_c/R_s = 2$). 100 nodes are distributed over a 500 meters x 500 meters area. It is shown that SWR has low energy consumption in routing compared to the other algorithms.

In the second scenario, target detection and tracking system is simulated. Nodes send the captured acoustic voice data to the sink to be analyzed. It is assumed that sink can analyze these acoustic voice data and determines the identity or classify the source of the noise. Sensor nodes can capture the acoustic noise up to 500 meters in depth by listening at 10-400 Hz. This noise is produced by the engine of the ship and is accepted as noise signature (fingerprint) of a ship. Other noises which are produced by the propeller, cavitations, and the movement of the ship on the surface or in the sea can only be listened at higher frequencies which are hard to capture and gives no idea about identity of the ship. Nodes are distributed over a 1000 meters x 1000 meters area and have transmission range of 200 meters. The target crosses the operation area with a constant speed and direction at 100 meters depth. Nodes send the target detection data packets to the sink during the period they detect the target. Voice data packets in terms of signature are only sent in case of sink requests them.

C. Compared Protocols

The proposed approach is compared with known benchmark protocols. One of the benchmark of all geographical routing protocols is the Greedy Perimeter Stateless Routing (GPSR) protocol which is also a stateless geographical routing protocol [9]. However, it uses neighborhood topology information for packet forwarding in greedy manner. GPSR collects the local topology (neighborhood) information by periodic beaconing messages. The most well-known routing algorithm is flooding. Actually most of the routing protocols for WSN and ad hoc networks are the variants of flooding with some modifications and optimizations. Flooding is the simplest stateless routing protocol since it does not require any routing table. The original data packet traverses on every path in the network including the shortest one which makes it the most reliable routing protocol. We also compare the results with a real-time protocol called SPEED [10]. The results are also compared with an imaginary routing protocol which is called as virtual optimal routing protocol. It is assumed in this protocol that it has not any routing overhead. Data packets are carried over optimal path towards the destination. Therefore, the transmissions and the energy consumption will remain minimal. Such a protocol provides a good comparison about effectiveness of the proposed protocols by also comparing other performance metrics.

D. Energy Consumption

Fig. 3 shows the system-wide consumed energy values in routing process in scenario 1 during the lifetime of the protocols. Lifetime is considered as the first failure on finding any route to the destination. GPSR and SPEED protocols and the flooding algorithm deplete the allocated energy very quickly. Their lifetimes are very close, 124 seconds, 125 seconds, and 165 seconds for SPEED, GPSR, and flooding respectively. SPEED and GPSR deplete most of their energy at the beaconing, while the flooding depletes its energy on routing process. The overall system energy of the GPSR protocol is slightly higher than flooding. However, flooding has longer lifetime because it uses every path at once to reach the destination. Node terminations do not affect flooding if there is a path to the sink. The SWR protocol continues to live when the simulation ends after 900 sec. When compared with the Virtual Optimal Routing, energy consumption in the SWR is close to the energy consumption in Optimal Routing. In the SWR, the energy is consumed only in routing processes.

E. Reliability

Upon collisions, link failures, node movements or node terminations, the lost packets are required to be retransmitted. Retransmissions introduce delay and consume energy and bandwidth. In some cases, it yields route breakage and even the destination may become unreachable. Therefore, in the second scenario, the reliability of the protocols is compared with the existing ones. Packets loss rates are set as 5, 10, 15, 20, and 25% to observe route breakages and unfound paths. Fig. 4 indicates the ratio of broken routes to the total routes that would be found. SPEED, GPSR, and even the Virtual Optimal Routing protocol show a high increase of broken routes as the packet loss rate increases. For packet loss rate 5%, they are very close to each other with 10-13% rates. As the packet loss rate increases, broken route rates reaches to 80% for GPSR and SPEED, and 60% for Virtual Optimal Routing. The dominating reason of these high ratios is that these protocols use single-path to convey the packet to the destination. Due to the movement of the nodes, packets do not arrive to the addressed nodes. Another reason is the node terminations that occur in SPEED and GPSR. On the other hand, the SWR and flooding are not affected from the mobility of nodes since they convey the packet on multiple paths.

Fig. 5 shows the ratio of unfound paths to the total routes that would be found. It is found that ratio of unreachable destinations remains almost the same for each protocol as the packet loss rates increase. Increase in packet loss rate does not affect the ratio of unfound paths in the SWR and Virtual Optimal Routing. Flooding is affected because node terminations occur due to energy depletion leaving the destination unreachable in course of simulation time. On the other hand, Virtual Optimal Routing protocol finds routes to the destination (Fig. 5) in spite of a high rate of broken routes (Fig. 4). GPSR and SPEED have a rate of 15% for unreachable destinations.

Table III shows the number of paths constructed between the source and the destination. Multiple paths provide reliability. GPSR, SPEED and Virtual Optimal Routing always find only one path which is the shortest one. Flooding constructs 13 paths during a long portion of the simulation but when the nodes begin to terminate, number of the paths reduces. When the sink node is hardly reachable due to node terminations around sink, only two paths are constructed in flooding. In the SWR, the number of the paths depends the distance between the source and the destination [2]. If the distance is short e.g. one hop away, only one path is constructed. As the distance between the source and the destination increases, the number of the paths constructed by multi-hopping increases.

F. End-to-End Delay

Fig. 6 shows the end-to-end delay on data packet transmissions. For GPSR, SPEED and Virtual Optimal Routing, end-to-end delay increases as the packet loss rate increases. The reason is that packet losses on transmissions cause route breakages. In such cases, packets are retransmitted. Retransmissions increase the end-to-end delay. The SWR has the minimum end-to-end delay the same as flooding because it has the forwarding mechanism similar to flooding. Because of the multiple path construction in the SWR, route breakages do not occur. Even at high packet loss rates (25%), the SWR preserves end-to-end delay at a stable value. This indicates that the SWR would provide time-limitations for the transmission of time-critical data.

V. CONCLUSIONS

In this paper, a reliable communication approach for instantly deployed sensor networks is proposed. Military applications in hostile environments and detection systems in critical areas require reliability and low delay for data transfer. However, provision of these requires excessive energy consumption. The

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method presented in this paper, provides reliability with an energy-efficient method. Reliability is provided by using multiple paths. Data is transported over multiple paths to compensate the requirements for reliability and obey time boundaries. On demand route construction and stateless property avoids the possible delay at nodes. Priority scheme and silence usage support real-time data traffic. Routing overhead and energy consumption is low due to the stateless property of the applied routing algorithm the SWR.

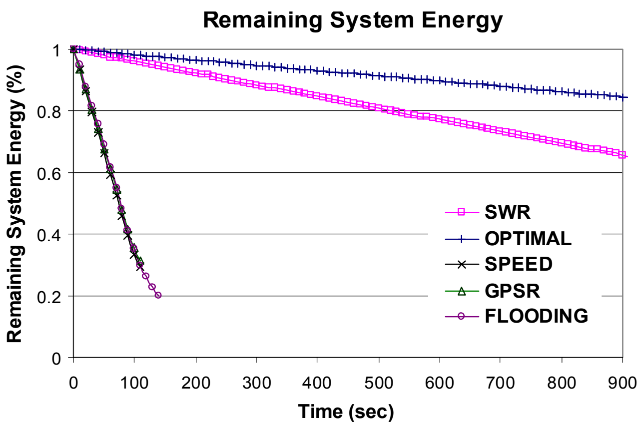

Figure 3. Remaining system energy levels of the protocols in scenario 1.

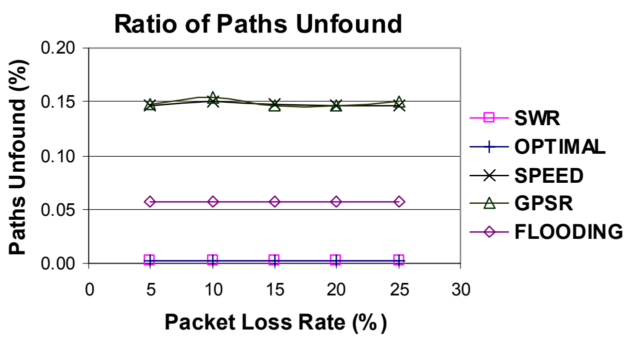

Figure 4. Ratio of the broken routes in scenario 2.

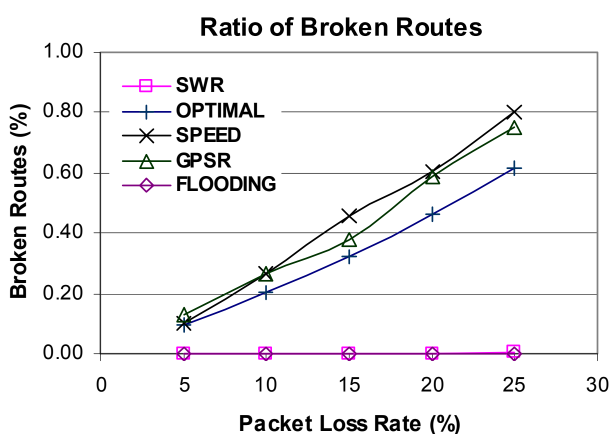

Figure 5. Ratio of the unfound paths in scenario 2.

TABLE III. COMPARISON OF THE NUMBER OF CONSTRUCTED PATHS PER DATA DELIVERY.

Routing Protocol	Number of Constructed Paths per Data Delivery			
	1 hop distant	2 hop distant	3 hop distant	4 hop distant
Flooding	2-13	2-13	2-13	2-13
GPSR	1	1	1	1
SPEED	1	1	1	1
Optimal	1	1	1	1
SWR	1	2	2-3	3-4

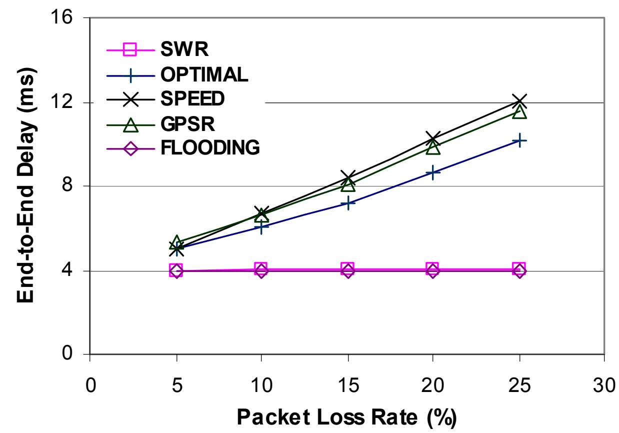

Figure 6. End-to-end delay in scenario 2.

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