Fault Tolerant Routing For Wireless Sensor Grid Networks

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Abstract ***– Wireless sensor networks technology provides an opportunity for innovation. It also brings unique challenges. Fault tolerant routing is a critical task for sensor networks operating in dynamic environments. In this paper, we present an experimental study on fault tolerant routing for wireless sensor grid networks. A network may be separated into partitions owing to the broken radio links resulted from the node failures. Since the leveling algorithm works effectively for unpartitioned network, a combined technique with extended transmission range is investigated to resolve the network partitioning problem. The experimental results show this technique reduces the probability of network partitioning significant. It also demonstrates near optimal network coverage and coverage efficiency with random dead nodes distributions.***
Keywords – *wireless sensor networks, network coverage, fault tolerant routing, leveling algorithm*

I. INTRODUCTION

Wireless sensor networks represent an emerging technology that has become very appealing to researchers. It is considered as a next generation technology to bridge between the Internet and the physical world. In recent years, many routing protocols have been successfully developed for different applications of wireless sensor networks. Direct diffusion is a data-centric routing protocol that is developed for information dissemination in sensor networks [1]. Low-energy adaptive clustering hierarchy (LEACH) is a well-known cluster-based algorithm [2]. Greedy perimeter stateless routing (GPSR) is a geographic routing protocol [3]. A comparison of many other existing protocols is available in [4]. Most of the above routing protocols were focused on the effective information retrieval with the emphasis on energy efficiency for sensor network.

In this paper, we present an experimental study on fault tolerant routing for wireless sensor grid networks. Leveling algorithm is presented as an energy efficient approach with automatic routing path update for unpartitioned network. Extending transmission range is proposed for effective network coverage in partitioned network. These two methods are then combined to provide a robust, fault tolerant routing scheme for wireless sensor grid networks.

The rest of the paper is organized as follows: Section 2 introduces the network topology of the application-specific wireless sensor grid, and then describes the details of the proposed fault tolerant routing algorithms. In Section 3, we provide the performance analysis of the proposed fault tolerant routing scheme. The experimental results are listed in Section4, followed by the conclusion in Section 5.

II. FAULT TOLERANT ROUTING ALGORITHMS

Wireless sensor networks have been applied in a variety of industrial, medical, and military applications. A large number of sensor nodes can be distributed in various topologies. For security or environmental sensing applications in urban area, one of the most convenient deployments is to attach the sensor nodes with the roadway streetlights. The sensor nodes are distributed along streets and avenues as in a geographic road map. Therefore, the network becomes a grid, called wireless sensor grid networks. Figure 1 shows an example of wireless sensor grid network. We randomly pick a node to serve as the data sink and assume that the data processing center is located at that node. For fault tolerance study, sensors nodes are randomly selected as dead nodes with a certain probability.

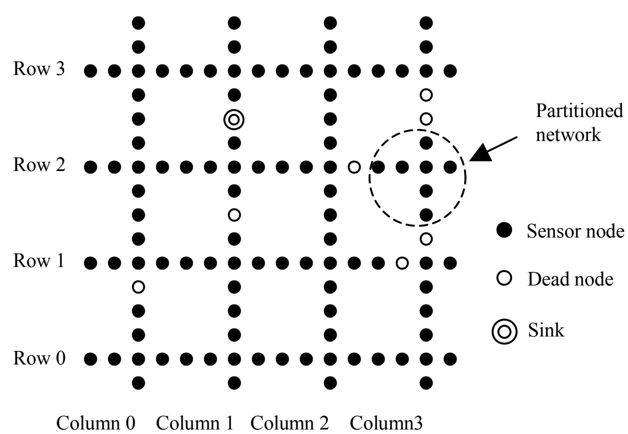


Fig. 1. An example of the wireless sensor grid network

In dynamic environment of senor networks, some nodes can be failed due to a variety of reasons including power depletion, circuit malfunction, processor failure, unreliable radio links, and etc. The aim of fault tolerance routing is to maintain the effective network coverage and undisrupted information retrieval from the field. In fault tolerant routing, the absolute node coverage, as the percentage of the live nodes over the total number of nodes, is less of the interests.

It is more important to consider the actual network coverage and the coverage efficiency. The definitions of these two parameters are given below:

Network coverage is defined as the total number of active nodes over the total number of nodes in the network. There exists at least one routing from an active node to the sink.

$$network\_coverage = \frac{n-d-L}{n} \quad (1)$$

Where n is the total number of nodes, d is the number of dead nodes, and L is the average number of inactive nodes in the network.

Coverage efficiency is defined as the number of active nodes over the number of live node. If there is no routing path from a live node to the sink, the live node is considered inactive.

$$coverage\_efficiency = \frac{n-d-L}{n-d} \quad (2)$$

A. Leveling algorithm for unpartitioned network

Leveling algorithm is proposed as an effective, low-complexity routing technique for unpartitioned network. In this algorithm, each node is assigned with a level value that indicates the distance hops to the data sink. During the initial setup phase, the level values of all nodes are set as infinity. The data sink first initiates a RREQ message to its neighbor and indicates a level value of zero. The neighbor nodes receiving this message change their level value to 1 and send the RREP message. The same procedure quickly propagates through the entire network, similar to the initial route discovery as in AODV [6]. The process is naturally analog to the water flowing from the high elevation to lower level, thus we called it the leveling algorithm. When some nodes become dead in the network, the level algorithm is able to automatically update the routing paths by changing the level values. The detail procedure for the adaptive leveling routing algorithm is listed below:

1. Set the level value of the dead nodes to infinity.
2. For any given node with level m, there exists at least one neighbor node whose level value is m-1 (except for the base station with zero value). Suppose the smallest level value of all neighbors is n. If $n = m - 1$, the current node value remains; If $n < m - 1$, the current node value is set as n+1; If $n > m$-1, the current node level is set to infinity.
3. The same rule above is applied to every node repetitively until the network converges. The convergence time and the route maintenance overhead are determined by the number of dead nodes as well as their locations in the network.

However, the leveling algorithm is limited to the unpartitioned networks. A partitioned network implies a certain area of the network that contains one or more live nodes but has no connection to the outside of the area as illustrated in Figure 1. When the leveling algorithm converges, the level values of all these isolated nodes turn into infinity that implies no valid path is available from the node to the data sink. It is imperative to develop an improved algorithm that can overcome such scenario.

B. Extending range method

A heuristic approach to solve the partitioned network problem is to increase the transmission power and to extend the communication range of the nodes as needed. As in the wireless sensor grid network showed in Figure 1, a live node with level value m should have one or more next hop node located as the immediate neighbor with the level of m-1. If a node detects that there is no next hop node available due to node failure, a straightforward approach is to increase its transmission power to extend the communication range. Due to the concern of energy consumption, the power increment is limited to four times of the minimum transmission power in this paper that result in a doubled communication range according to the path loss model [2]. Equivalently, it provides the additional ability for the active nodes to skip any single dead node along the routing path.

In practice, we allow a node to extend its transmission range immediately upon detecting the dead next hop node. Since the routing paths in the network largely remain intact, the route maintenance overhead is low. However, the extending range method has the disadvantage of exhaustive energy consumption, and is lack of routing flexibility. It simply extends the communication range of affected nodes, but does not perform route discovery to update the routing table of other nodes in the networks. Therefore, it does not guarantee that all physically reachable nodes can be routed to the data sink through the active routing paths for a partitioned network.

C. The combined technique

We consider a combination of the above two methods in this section. The route maintenance procedure is initiated from the data sink with a zero level value. If there is no next hop available among the directly connected neighbor nodes, range extension is requested. Consequently, local routing path update is performed immediately after each range extension. These two procedures are executed alternatively while the routing path maintenance propagates through the entire networks. For validation purpose, the same process is repeated and the node level value is updated if a shorter path is available. It is worth to mention that the combined technique is a greedy algorithm that converges quickly. It guarantees that all reachable nodes will be connected upon completion of the algorithm. However, the updated routing path does not necessarily reflect the lowest power consumption and minimum number of hops from each node to the data sink.

III. ANALYSIS

We analyze the proposed scheme in this section. First, the following denotations are used throughout our analysis:

N: total number of working sensors;

L: total number of levels in the networks;

L_i: the level of sensor i, assuming the data sink has the level value of 0;

N_i: the number of nodes at level i;

S_{data}: number of bits of information generated by each working sensor per sampling time period. All these information need to be transmitted toward the data sink. Data aggregation may take place;

O_{data}: number of bits of a packet header;

S_{max}: maximum payload length of a packet. Generally, $S_{max} > S_{data}$

r_c: compression ratio due to data fusion. This is the ratio of aggregating similar results into a more compact packet. $r_c < 1$;

r_t: data transfer rate for every node in the network (bits/sec)

T_o: total transmission overhead in bits;

T_f: total traffic in the network per unit time;

Assuming each sensor carries out the same amount of sensing tasks, every node generates the same data rate. The total data payload of the network is $N*S_{data}$.

In the fully-connected network approach, where each working sensor sends data towards the data sink directly. Since each node sends a packet to the data sink, the total transmission overhead is,

$$T_o = O_{data} N \quad (3)$$

The total traffic of the fully-connected network is,

$$T_f = (S_{data} + O_{data}) N \quad (4)$$

The total data transferring time is,

$$T_{trans} = N(S_{data} + O_{data}) / r_t \quad (5)$$

Using the leveling algorithm, the total transmission overhead is the same as $O_{data}N$, without considering the maximum payload length of a packet. It is assumed that every node only transmits once in each data acquisition time period. The total traffic is,

$$T_f = \sum_{i=1}^{N} S_{data} r_c^{(Li-1)} + O_{data} N \quad (6)$$

For a sensor at level L_i, The payload S_{data} is compressed (Li-1) times along the path to the data sink. The first-level does not perform data compression, because there is no data aggregation.

For the leveling method, the data transfer time is determined by the number of levels L, the information generation rate at every sensor node Sdata, and the number of nodes on each level N_i, where

$$N = \sum_{i=1}^{L} N_i \quad (7)$$

Assuming uniform network distribution, the total data transferred in the network is,

$$T_f = \sum_{i=1}^{L} N_i S_{data} r_c^{\ i} \quad (8)$$

where r_c is data compression ratio due to aggregation. No data aggregation occurs at outer level L. The average data transmission rate for a node at level i is,

$$T_i = \frac{1}{N_i} \sum_{j=i}^{L} S_{data} N_j r_c^{L-j} \quad (9)$$

Given the maximum packet payload length S_{max}, the number of packets per node at level i is,

$$M_i = \left\lceil \frac{1}{N_i S_{max}} \sum_{j=i}^{L} S_{data} N_j r_c^{L-j} \right\rceil \quad (10)$$

For uniform sensor network, the total number of packets transferred in the network is,

$$M_{packet} = \sum_{i=1}^{L} N_i \left\lceil \frac{\sum_{j=i}^{L} S_{data} N_j r_c^{L-j}}{N_i S_{max}} \right\rceil \quad (11)$$

The total transmission overhead is,

$$T_o = O_{data} M_{packet} \quad (12)$$

The total data transfer time is

$$T_{trans} = \frac{\sum_{i=1}^{L} \frac{1}{N_i} \sum_{j=i}^{L} S_{data} N_j r_c^{L-j} + M_{packet} O_{data}}{r_t} \quad (13)$$

IV. EXPERIMENTAL RESULTS

The experimental setup of the wireless sensor grid network is shown as in Figure 1, with 4 rows and 4 columns and a total of 112 sensor nodes. The case with a single data sink is considered and the location of the data sink is randomly selected. The transmission distance for the leveling algorithm is one hop, and the extending range is up to two hops. The simulation code for all three algorithms is developed in Matlab. For each algorithm, the experimental results are obtained by varying the number of dead nodes in the network. The locations of the dead nodes are randomly selected. Each case has been simulated with a total of 10^7 iterations.

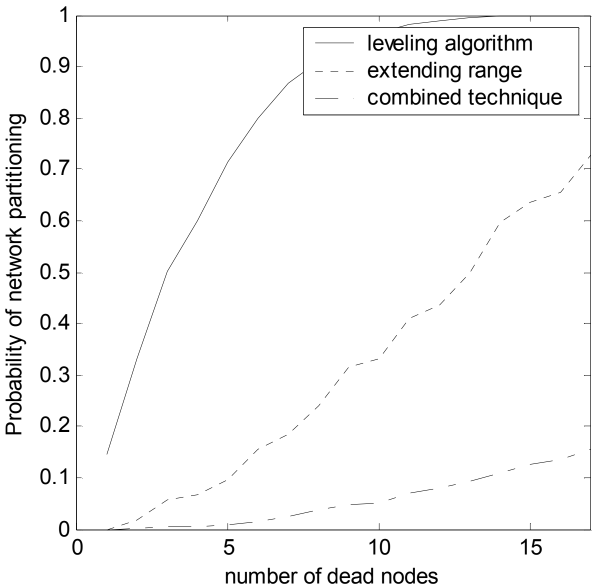
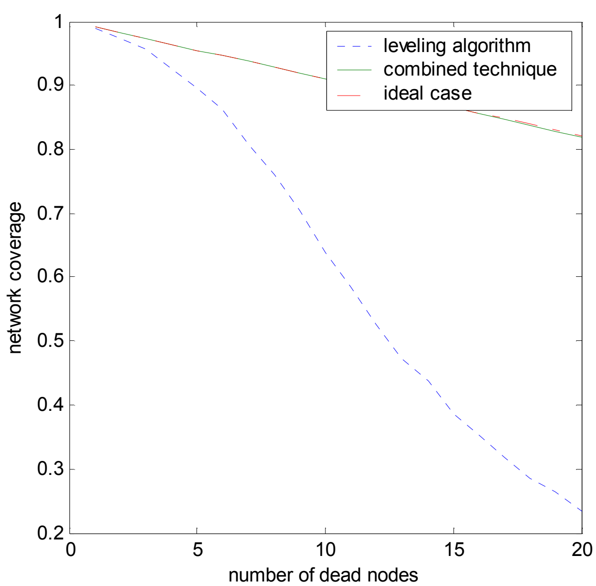
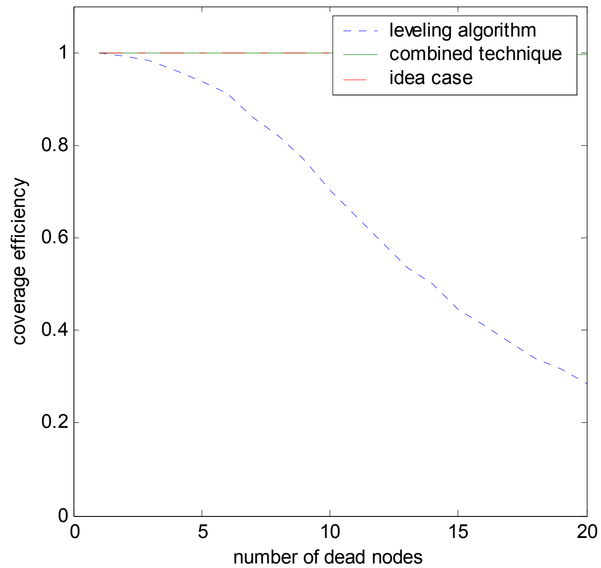


Fig. 2. Probability of network partitioning

Figure 2 shows the probability of partitioned network increases as the number of dead nodes grows for all three algorithms. Result of the leveling algorithm shows the probability of partitioned network reaches 99% with only 12 dead nodes. While the extending range method reduces the probability, the combined technique is a significantly better approach to avoid network partitioning.



(a)



(b)

Fig. 3. Performance comparisons (a) network coverage comparison (b) coverage efficiency comparison

Figure 3 shows that the combined technique can achieve better performance than the leveling algorithm in fault tolerant routing. Known the number of active nodes and their locations, the ideal network coverage and coverage efficiency can be computed. Result of the combined technique is approaching the idea case.

V. CONCLUSION

This paper presents an experimental study on fault tolerant routing algorithms for wireless sensor grid networks. First, leveling algorithm is proposed as an energy efficient method for route discovery and maintenance. Secondly, extending the transmission range method is presented to overcome limited performance of the leveling algorithm on partitioned network owing to the dead node. Lastly, a combination of these two techniques is investigated to reduce the probability of network partitioning. The simulation results show that the combined technique significantly improves the communication in partitioned networks. It provides s better performance in network coverage and coverage efficiency as well. For future work, the balance of node energy consumption will be investigated for the proposed techniques. The extension for multiple data sinks will also be studied.

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REFERENCES

[1] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Direct diffusion: a scalable and robust communication paradigm for sensor networks," in *Proceedings of MobiCom,* August, 2000.

[2] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Transactions on Wireless Communications*, vol. 1, no. 4, pp. 660-670, October 2002.

[3] B. Karp and H. T. Kung, "GPSR: greedy perimeter stateless routing for wireless networks," in *Proceedings of the MobiCom*, August, 2000.

[4] A. Ahmed, H. Shi and Y. Shang, "A survey on network protocols for wireless sensor networks," in *Proceedings of the International Conference on Information Technology*, pp.301–305, August, 2003.

[5] Y. Xue and K. Nahrstedt, "Fault Tolerant Routing in Mobile Ad Hoc Networks," In *Proceedings of IEEE Wireless Communication and Networking Conference*, pp. 1174-1179, March, 2003.

[6] E. Royer and C. Toh, "A review of current routing protocols for ad-hoc mobile wireless networks," *IEEE Personal Communications Magazine*, pp. 46–55, 1999.