Performance Analysis of Dual-Homed Fault-Tolerant Routing in Wireless Sensor Networks

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***Abstract*— One of the fundamental purpose of sensing information is to immediately respond to any anomalies. In order to make an accurate and cognizant decision, there is a great need for a fault-tolerant wireless sensor network. In this paper, we evaluate two categories of dual-homed routing for providing fault-tolerance in wireless sensor networks, namely *dedicated dual-homed routing* and *shared dual-homed routing*. We investigate two dedicated dual-homed routing techniques, namely *1+1 dual-homed routing* and *1:1 dual-homed routing*. We also develop shared dual-homed routing techniques, namely *1:2 dual-homed routing* and *1:4 dual-homed routing*. This paper investigates each technique's capability for providing fault-tolerance and its performance in terms of network lifetime, packet loss probability, end-to-end packet delay, and average throughput. Such an investigation will provide a comprehensive understanding about each proposed fault-tolerant technique. This will provide valuable insight for providing grade-of-protection in multi-layer wireless sensor networks by applying different techniques at different layers.**

Keywords: Wireless Sensor Networks, Fault-Tolerance, and TDMA.

I. Introduction

The next-generation networks are envisioned to be deployed as an infrastructure of devices that are available anywhere and any time, autonomous, survivable against multiple faults and attacks, and highly secure for communication. Recent advances in wireless communications and electronics have enabled the development of low-cost, low-power, small-size, and multi-functional sensor nodes [1]. Such tiny sensor nodes have led to the emergence and deployment of wireless sensor networks. A typical wireless sensor network, consists of one or more sink nodes and many sensor nodes scattered across a sensing site.

Clustered or layered structures have been particularly appreciated in building large-scale sensor networks [2], [3], [4], [5], [6], [7]. The low-energy adaptive clustering hierarchy (LEACH) [2] protocol randomly selects sensor nodes as the cluster-heads so that high energy dissipation for communicating with the base station is spread to all sensor nodes across the sensor network. All the data packets originating in the cluster are forwarded towards the cluster-head. Cluster-head in turn will forward these packets towards destination. The hybrid energy-efficient distributed (HEED) clustering algorithm improves LEACH with a better cluster-head distribution through a periodical selection of cluster-heads according to a hybrid function based on node's residual energy and a secondary parameter, such as node proximity to its neighbors or nodal degree [3]. The robust energy efficient distributed (REED) clustering algorithm achieves k-fault tolerance by selecting k independent sets of cluster-heads [4]. In [5], the multi-hop infrastructure network architecture (MINA) is proposed for the organization of large-scale sensor networks. This approach partitions sensor nodes into different layers according to their individual hop counts to the sink node.

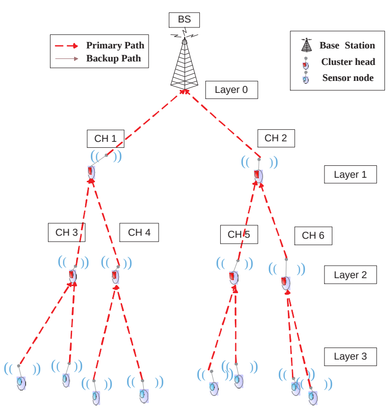


Fig. 1. Multi-layered architecture.

Consider a large-scale heterogenous network as shown in Figure 1 with possibly thousands of sensor nodes organized into multiple layers. The cluster-heads fuse data sent from each sensor node within its cluster in order to minimize the energy spent on data transmission. This aggregated information is now transmitted to the next higher-layer cluster-head as the data makes its way toward the base station. It is critical that this data packet reaches the base station, since the loss of a single packet eliminates the information sensed by a whole (possibly large) sub-tree of sensor nodes. Thus, providing protection for the cluster-head at higher layers is critical.

The concept of dual-homing [8] is widely used in the Internet to provide fault-tolerance against node and/or link failures. In this paper, we propose five different dual-homed fault-tolerant routing techniques. We limit our study to the performance evaluation of several dual-homed fault-tolerant routing techniques, after the dual-homes have been selected. The problem of selecting the optimal dual-homes is an interesting problem in itself and is outside the scope of this paper. We also adopt TDMA-based MAC for intra-cluster and inter-cluster communication in the multi-layered WSN.

To provide fault-tolerance in wireless sensor networks multipath routing [9], [10] and reliable transport protocol [11] has been proposed for flat-grid networks. Multipath routing technique aims to find multiple disjoint (or braided) paths between the source and the destination through routing discovery protocol. Most reliable data transport protocols in wireless sensor networks require hop-by-hop acknowledgement. This leads to a fault-tolerance design that is not scalable. Our proposed dual-homed fault-tolerant routing is to provide a backup cluster-head for each cluster in the existing hierarchical topology. Since fault-tolerance can be provided at selected layers, only a local change is necessary to provide scalable fault-tolerance in a multi-layer wireless sensor network. The rest of the paper is organized as follows: Section II describes several dual-homed routing techniques for supporting fault-tolerance in wireless sensor networks. Section III presents our simulation results and Section IV concludes the paper.

II. Dual-Homed Fault-Tolerant Routing

For dual-homed fault-tolerant routing design, each cluster-head can either have a dedicated backup cluster-head (at the same layer) or have a backup cluster-head shared with other cluster-heads. The traffic can be only sent to one cluster-head or it can be sent to both primary and backup cluster-heads simultaneously. Based on different combinations, we can classify the dual-homed fault-tolerant routing techniques into dedicated 1:1 dual-homed routing, dedicated 1+1 dual-homed routing, and shared dual-homed routing. We now discuss different dual-homed fault-tolerant routing techniques.

A. Dedicated 1+1 Dual-Homed Routing

In 1+1 *dual-homed routing* (1+1 DHR), each cluster has two dedicated cluster-heads and the data is sent to both the primary cluster-head (primary home) and the backup cluster-head (backup home) simultaneously. The primary cluster-head and the backup cluster-head use TDMA to receive data and the time slot assignment for each sensor node in the cluster is the same for both the primary cluster-head and the backup cluster-head. Fig. 2(a) demonstrates the working principle of 1+1 dual-homed fault-tolerant routing. Each cluster at the lowest-layer, Layer 3, has dedicated primary and backup higher-layer cluster-heads at Layer 2. Sensor nodes in Layer 3 send data to both primary as well as backup cluster-heads at any given time instant (CH3P/3B, CH4P/4B, CH5P/5B, and CH6P/6B). In Fig. 2(a), we assume that there is no protection above Layer 2. Cluster-heads at Layer 2 send data to their Layer 1 cluster-heads (CH3P/3B/4P/4B to CH1 and CH5P/5B/6P/6B to CH2, respectively). Finally, the Layer 1 cluster-heads (CH1 and CH2) in turn forward the data to the base station. Once the packets reach the base station, the base station can filter the redundant packets based on the packet sequence number.

We observe that 1+1 DHR technique can provide fault-tolerance against failure of one cluster-head (primary or backup) per cluster. If the primary cluster-head fails, data can be sent to the sink through backup cluster-head transparently and seamlessly. The disadvantage is that both the primary cluster-head and the backup cluster-head participate in the data dissemination, which potentially reduce the time that they can offload each other by rotation in regular non-redundant data dissemination. On the other hand, duplicated packets forwarded to the higher-layer increases the system load, leading to reduced network lifetime and higher packet loss.

B. Dedicated 1:1 Dual-Homed Routing

In 1:1 *dual-homed routing* (1:1 DHR), each cluster has two dedicated cluster-heads. One serves as the primary cluster-head and the other serves as the backup cluster-head. Data from the cluster-members is only sent to the primary cluster-head, when the primary cluster-head is in operation. Data will be sent to the backup cluster-head only when the primary cluster-head has failed. In 1:1 DHR, the primary cluster-head uses TDMA to receive the data from its cluster-members. Meanwhile, the primary cluster-head also needs to notify the backup cluster-head with the TDMA schedule for each sensor in its cluster. When the primary cluster-head fails, the backup cluster-head will take up and receive the data from its cluster-members. All the data from the cluster will be shifted to the backup cluster-head. Fig. 2(b) demonstrates the working principle of 1:1 dual-homed fault-tolerant routing. Each primary cluster-head at Layer 2 has a dedicated backup cluster-head (CH3P/3B and CH4P/4B). At the lowest layer, Layer 3, sensor nodes (cluster-members) send data to their corresponding primary cluster-heads (CH3P, CH4P, CH5P, and CH6P) until they fail. In the event of a primary cluster-head failure, all members of the corresponding cluster will now route data through its backup cluster-head (CH3B, CH4B, CH5B, and CH6B). Cluster-heads at Layer 2 send data to their Layer 1 cluster-heads (CH3P/3B/4P/4B to CH1 and CH5P/5B/6P/6B to CH2, respectively). Finally, the Layer 1 cluster-heads (CH1 and CH2) in turn forward the data to the base station.

We observe that 1:1 DHR technique is transparent to the source sensor nodes, since sensors do not need to change their time slot assignments for transmission. The only coordination necessary is that the primary cluster-head needs to share certain information with the backup cluster-head. There are two possible solutions to notify the backup cluster-head about the failure of primary cluster-head. One solution is that the backup cluster-head continually monitors the behavior of the primary cluster-head (unplanned failure). The other solution is that the primary cluster-head should notify the backup cluster-head when it is about to deplete its energy (planned failure). In either case, there might be some data loss during the handover from the primary cluster-head to the backup cluster-head.

C. Shared 1:2 Dual-Homed Routing

In 1:2 *dual-homed routing* (1:2 DHR), for every two primary cluster-heads we have a single backup cluster-head protecting them. Each cluster has one dedicated primary cluster-head and one shared backup cluster-head. Similar to 1:1 DHR, in 1:2 DHR data from the cluster-members is sent only to the primary cluster-head as long as the primary is in operation. Data will be sent to the backup cluster-head only when the primary cluster-head has failed. Fig. 3(a) demonstrates the principle working of 1:2 dual-homed fault-tolerant routing. We have considered fault-tolerance at Layer 2 only. Each primary cluster-head at Layer 2 shares a backup cluster-head (CH3 and CH4 share CH3B/4B and CH5 and CH6 share CH5B/6B). At the lowest-layer, Layer 3, sensor nodes (cluster-members) send data to their corresponding primary cluster-heads (CH3, CH4, CH5, and CH6) until they fail. In the event of a primary cluster-head failure, all members of the corresponding cluster will now route data through its backup cluster-head (CH3B/4B or CH5B/6B). Cluster-heads at Layer 2 send data to their Layer 1 cluster-heads (CH3, CH4, and CH3B/4B to CH1 and CH5, CH6, and CH5B/6B to CH2, respectively). Finally, the Layer 1 cluster-heads (CH1 and CH2) in turn forward the data to the base station.

Similar to dedicated 1:1 DHR, shared 1:2 DHR might experience data loss during the handover from the primary cluster-head to the shared backup cluster-head. The primary benefit of 1:2 DHR is the concept of sharing of backup cluster-heads to improve resource utilization and to incur lower network costs compared to the dedicated fault-tolerant routing techniques.

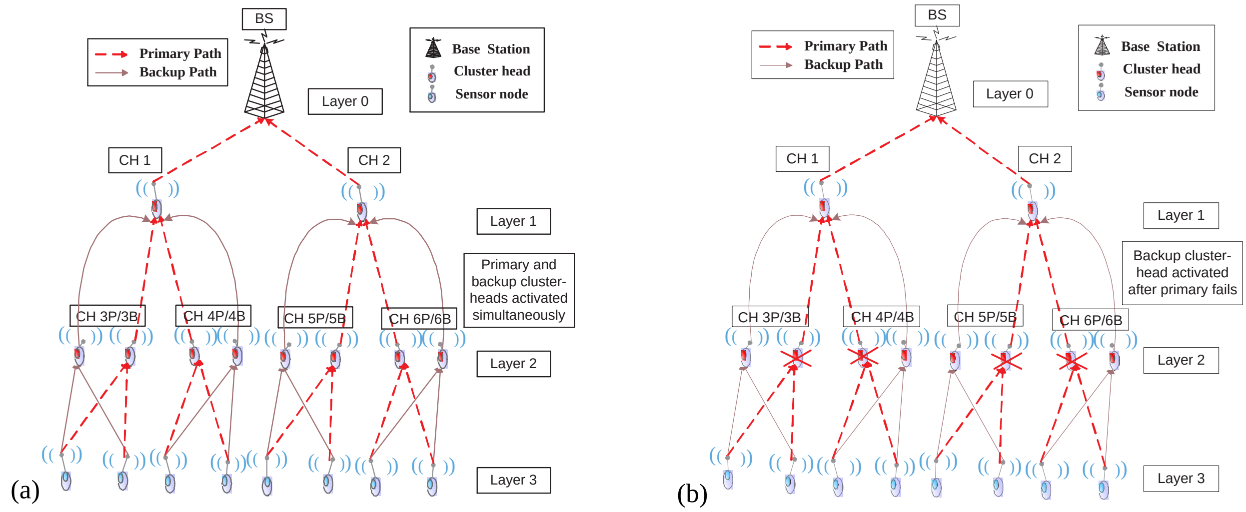


Fig. 2. (a) 1+1 dual-homed fault-tolerant routing and (b) 1:1 dual-homed fault-tolerant routing.

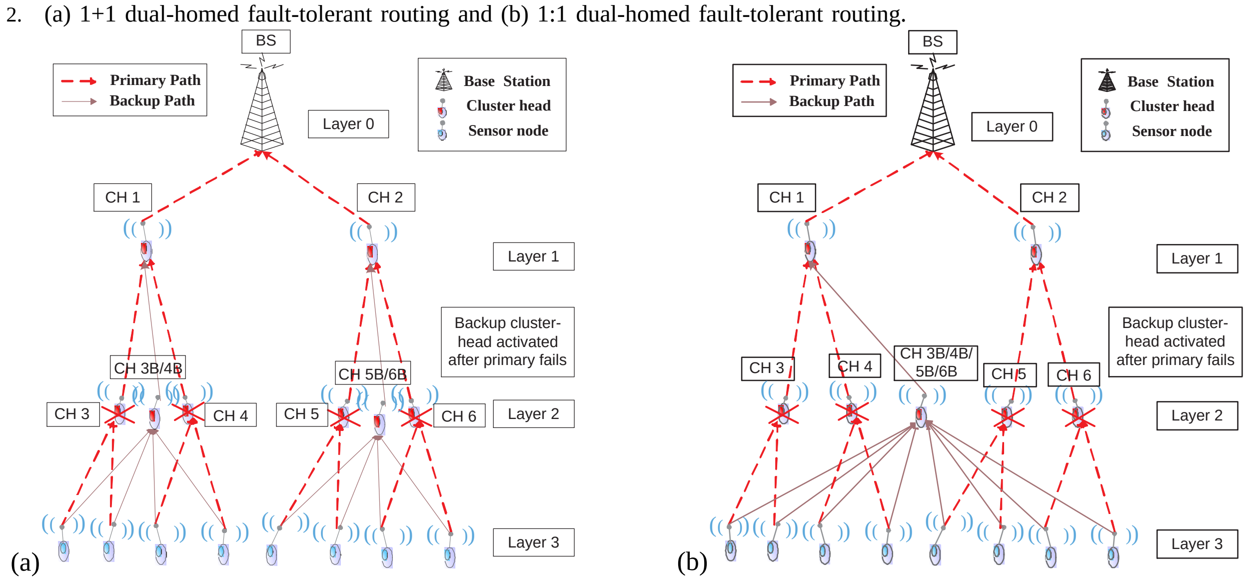


Fig. 3. (a) 1:2 shared dual-homed fault-tolerant routing and (b) 1:4 shared dual-homed fault-tolerant routing.

D. Shared 1:4 Dual-Homed Routing

In 1:4 *dual-homed routing* (1:4 DHR), for every four primary cluster-heads we have a single backup cluster-head protecting them. Each cluster has one dedicated primary cluster-head and one shared backup cluster-head. Fig. 3(b) demonstrates the working principle of 1:4 dual-homed fault-tolerant routing. Each primary cluster-head at Layer 2 shares a backup cluster-head (CH3, CH4, CH5, and CH6 share CH3B/4B/5B/6B). At the lowest layer, Layer 3, sensor nodes (cluster-members) send data to their corresponding primary cluster-heads (CH3, CH4, CH5, and CH6) until they fail. In the event of a primary cluster-head failure, all the members of the corresponding cluster will now route data through its backup cluster-head (CH3B/4B/5B/6B). Cluster-heads at Layer 2 send data to their Layer 1 cluster-heads (CH3, CH4, and CH3B/4B/5B/6B to CH1 and CH5, CH6 to CH2, respectively). Finally, the Layer 1 cluster-heads (CH1 and CH2) in turn forward the data to the base station.

E. Grade of Protection

The fault-tolerant routing techniques introduced above can provide different grades-of-protection based on affordable network resource and desirable protection level.

As discussed before, in a multi-layered wireless sensor networks with data fusion in order to prevent loss of critical information, more conservative protection approaches should be adopted at the higher-layers. It is highly recommended to apply dedicated 1+1 dual-homing routing in the higher-layers of the wireless sensor networks. We know that dedicated 1+1 dual-homed routing also introduces redundant data packets. Thus, if we apply dedicated 1+1 dual-homed routing in Layer i, more data packets are forwarded to Layer $i-1$, Layer $i-2, \ldots$, and Layer 0. We observe that it is appropriate to introduce dedicated 1+1 dual-homed routing in the higher-layers in order to reduce the overload as well as enhance reliability. Since the data in a wireless sensor network is usually time and spatial correlated, shared 1:4 or shared 1:2 dual-homed routing techniques can be applied in the lower-layer. Dedicated 1:1 dual-homed routing can achieve better fault-tolerance than a shared solution with affordable network resources. Dedicated 1:1 dual-homed routing can be applied in the middle-layers.

In a four-layer wireless sensor network, we can employ shared 1:4 dual-homing at lowest-layer, shared 1:2 dual-homing at the next-higher layer, dedicated 1:1 dual-homing at the next-higher layer, and dedicated 1+1 dual-homing at the highest-layer.

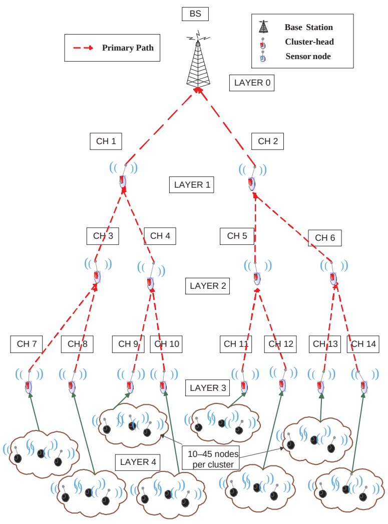


Fig. 4. 14 cluster-heads simulation network with up to 360 sensors.

III. Simulation Results

In order to evaluate the performance of our proposed routing techniques, we run simulations on a four-layered cluster-based hierarchical network wireless sensor network with 14 cluster-heads depicted in Figure 4. The wireless sensor network with 14 cluster-heads supports up to 360 sensor nodes. In order to compare the proposed dual-homed routing techniques, we define a baseline *single-homed routing* (SHR) technique. SHR employs traditional single-path (single-home) routing that is not tolerant against any node (or link) failure. In SHR (refer Figure 4), the each cluster (group of sensor nodes) at Layer 4 transmit packets to their respective cluster-heads (CH7, CH8, CH9, CH10, CH11, CH12, CH13, and CH14) at Layer 3. Layer 3 cluster-heads forward packets to cluster-heads at Layer 2 (CH7 and CH8 to CH3, CH9 and CH10 to CH4, CH11 and CH12 to CH5, and CH13 and CH14 to CH6, respectively). Layer 2 cluster-heads forward packets to cluster-heads at Layer 1 (CH3 and CH4 to CH1 and CH5 and CH6 to CH2, respectively). Finally, the Layer 1 cluster-heads forwards packets to the base station.

A. Simulation Model

We use NS-2 discrete-event simulator to evaluate the performance of the proposed routing techniques. The following are the important simulation assumptions: sensing site is 700 m by 700 m with 14 cluster-heads, up to 360 sensor nodes, and a base station. Hierarchical node addressing scheme [12], [13] is used to determine cluster-heads at each layer. The MAC protocol used is time division multiple access (TDMA); transmission range for all sensors is 550 m; packet size is 500 bytes. The power levels are as follows: transmission power is 24 mW, receiving power is 6 mW, and idle power is 0 mW. We set the same transmission power, receiving power, and idle power for all sensor nodes. We also set an initial energy of 2000 J for each sensor node, 1000 J for each Layer 2 and Layer 3 cluster-head, and 2500 J for the Layer 1 cluster-head and the base station. These energy values are preset so as to simulate Layer 2 partitioning before the failure of any other layer in the network. In our simulations, we implement fault-tolerant routing only at the Layer 2. The traffic arrivals are exponential with burst time and idle time equal to 500 ms. We use the term *data arrival rate* to represent the arrival rate of new data packets from each sensor node destined to the base station. We evaluate the performance of the proposed routing techniques for data rates from 10 Kb/s to 45 Kb/s from each cluster at Layer 4. Each cluster consists of number of sensor nodes with each node transmitting data at 1 Kb/s rate. The total number of sensor nodes in each cluster varies depending upon the value of the simulated data arrival rate, i.e., if the data arrival rate is 10 Kb/s, we have 10 sensors per cluster. Each cluster sends data to its respective Layer 3 cluster-head. These cluster-heads route the packets to their respective Layer 2 cluster-heads. These cluster-heads route the packets to Layer 1 cluster-heads, which then forward them to the base station using destination-sequenced distance vector (DSDV) [14], [15], [16] routing protocol. Each node that routes packets is assumed to have a queue with size of 50,000 packets. Simulation is executed for 50,000 seconds. Data fusion is generally desired to improve the overall lifetime of the wireless sensor network. We have not implemented data fusion at the cluster-heads in our simulations. It is important to note that the relative performance of all the routing techniques will remain the same with or without data fusion, and that data fusion is a basic energy-efficiency enhancement that can be applied to any routing technique. We are currently working on incorporating data fusion into our simulation.

B. Performance Results

In order to compare the performance of the different routing techniques, we evaluate them with respect to the following metrics:

- Network lifetime (in seconds): time until the network is completely partitioned due to the failure of all Layer 2 nodes.
- Average end-to-end packet delay (in seconds): ratio of the sum of individual end-to-end packet delays to the total number of packets successfully received. The delay components include queuing delay, propagation delay, and route-discovery delay.
- Average loss probability: ratio of total number of data packets dropped to sum of total number of data packets received at the base station and total number of data packets dropped (until end of simulation).
- Average throughput (in KB/s): ratio of total number of data (in bytes) successfully received at base station during the entire simulation to simulation time (in seconds).

In order to evaluate the performance of all the techniques in a fair manner, the simulation does not end until all the proposed techniques fail to provide fault-tolerance. Thus, the loss probability, the end-to-end delay, and the average throughput values are computed over the entire simulation time for each technique. As we shall see in Fig. 5, 1:1 DHR is the longest-living technique with the highest network lifetime. Hence, all simulations are run until the time the network partitions using 1:1 DHR.

Figure 5(a) plots the network lifetime versus data arrival rate for the different routing techniques. We observe that 1:1 DHR outperforms all other routing techniques at all data rates. In 1+1 DHR packets are routed simultaneously through both routes at all times, leading to increase in energy consumption (due to forwarding of duplicated packets leading to doubled

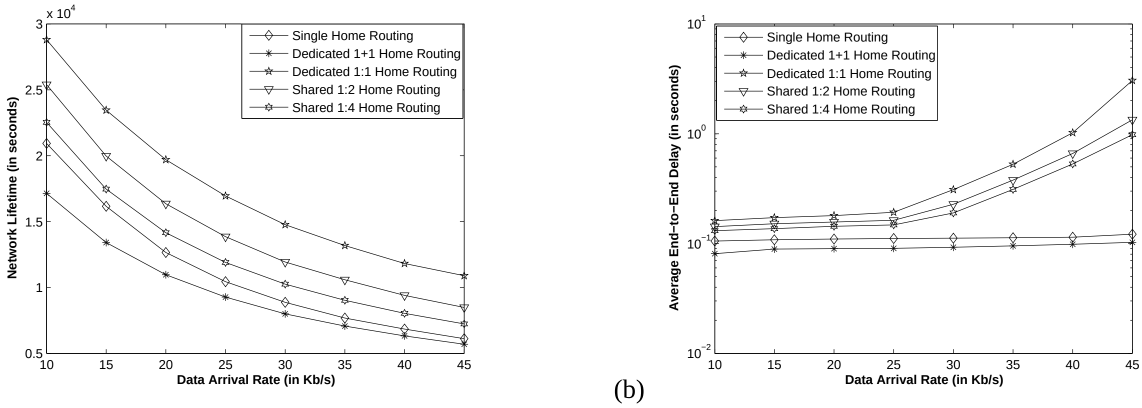


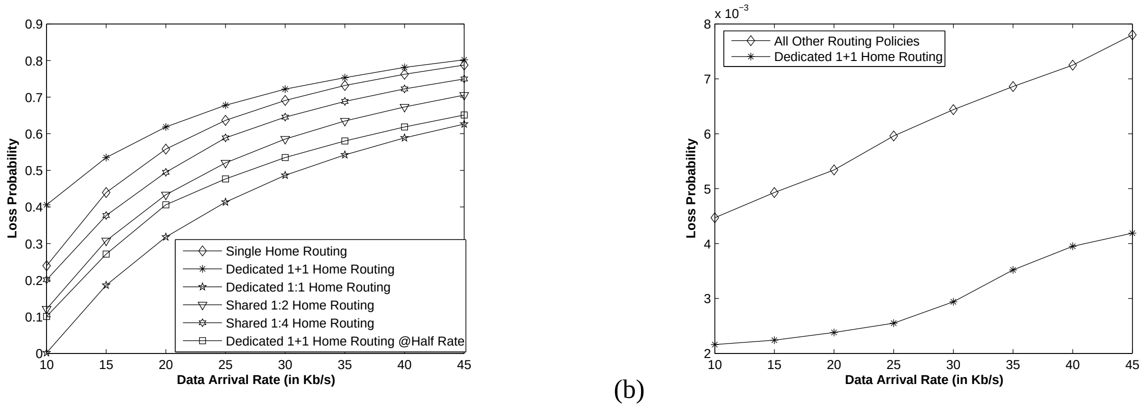
Fig. 5. (a) Network lifetime versus data rate. (b) Average end-to-end packet delay versus data arrival rate.

data rate at the layer 2 cluster-heads) and corresponding decrease in network lifetime as compared to all other techniques. In SHR, packets are routed through a single primary route, and the network is considered dead when all the cluster-heads at Layer 2 fail. In 1:1 DHR, data packets are routed through either primary or backup paths at all times, leading to minimal energy consumption and increased network lifetime (backup homes are activated after their primary fails). We also observe that shared dual-homed routing (1:2 and 1:4) provide reasonable increase in network lifetime by using limited additional network resources (backup cluster-heads). Sharing allows the network designer to choose an appropriate-level of fault-tolerance based on the amount of available resources and overall network deployment cost.

Figure 5(b) plots the average end-to-end packet delay versus data rate for different routing techniques. We observe that the average end-to-end delay of 1+1 DHR is the least. Note that the backup cluster-heads are placed slightly closer to the base station as compared to the primary cluster-head (delay on backup path is less than primary path). In 1+1 DHR packets are routed simultaneously through both routes at all times. At the base station, we receive the packet copy that arrives first and ignore the later arriving duplicate (packet with minimum delay is considered). In 1:1 DHR, initially data packets are routed through primary cluster-heads incurring a fixed delay. After the primary cluster-head failures, the end-to-end delay increases due to route discovery delay. We use DSDV to discover a new route from each dedicated backup cluster-head to the base station. The delay also increases with increase in data arrival rates, since the queueing delay also increases. In 1:2 and 1:4 shared DHR, after the primary cluster-head failure the delay induced due to the new route discovery from each backup cluster-head is lower than 1:1 DHR. This is due to the fact that, in shared DHR, route discovery has to be initiated with the first primary cluster-head sharing the backup cluster-head fails. For all other primary cluster-heads sharing the same backup cluster-head, the route on to the base station is already discovered. Thus, shared DHR result in reasonable decrease in average end-to-end delay using limited additional network resources as compared to dedicated DHR.

Figure 6 plots the loss probability versus data arrival rate for the different routing techniques. In our simulations, packet loss is primarily due to Layer 2 cluster-head failure. In order to evaluate the performance of the different techniques in a fair manner, the loss values are computed until number of seconds corresponding to the network lifetime of 1:1 DHR, i.e., the earliest point of time when all the techniques have failed. Fig. 6(a) shows the average packet loss probability versus data arrival rate for the different routing techniques. As the network lifetime of 1+1 DHR is the least, 1+1 DHR experiences the highest packet loss compared to all the other techniques. We observe that 1:1 DHR experiences the least loss probability and has the best loss performance for all the data rates considered. We also observe that the shared DHR techniques result in a reasonable decrease in loss by using limited additional network resources. Fig. 6(b) shows the average packet loss probability versus data rate for 1+1 DHR and all other routing techniques, until the latest time when all the routing techniques are active (no network partition). On close introspection, we observe that 1+1 DHR has the lowest loss probability while all the policies are active. Based on our initial definition, data arrival rate of 10 Kb/s at which each Layer 3 cluster-head holds true for all routing policies except 1+1 DHR. In 1+1 DHR, data rate gets doubled at the Layer 2 cluster-heads, since at any time instant both primary and backup cluster-heads are transmitting original and duplicate packets, respectively. This significantly drains the battery of all the Layer 2 cluster-heads leading to decreased network lifetime. Out of curiosity, we have also included a plot when the date rate of 1+1 DHR is halved, so as to maintain the same effective data rate for all routing techniques. Note that the sensing interval of the Layer 3 cluster-heads will have to be doubled to achieve the above and this modification may not be acceptable to certain sensing applications. We now observe that 1+1 DHR (at half-rate) has the better loss performance then all the other routing techniques except 1:1 DHR at all data rates considered.

Figure 7 plots the average throughput versus data arrival rate for the different routing techniques. We observe that at all data rates, 1:1 DHR performs the best, 1+1 DHR performs the worst, and shared DHR's performance is in-between SHR and 1:1 DHR. This is due to the fact that 1:1 DHR has the most network resources to begin with (same as 1+1 DHR) and the energy-consumption to route data packets during the lifetime of the network is minimal. At the other end, 1+1 DHR has the least throughput as each node has to waste additional energy to forward a duplicate packet for every original data packet. Thus, the average throughput is least in 1+1 DHR as compared



(a) (b)

Fig. 6. (a) Average packet loss probability versus data arrival rate. (b) Average packet loss probability versus data arrival rate for 1+1 DHR and all other routing techniques.

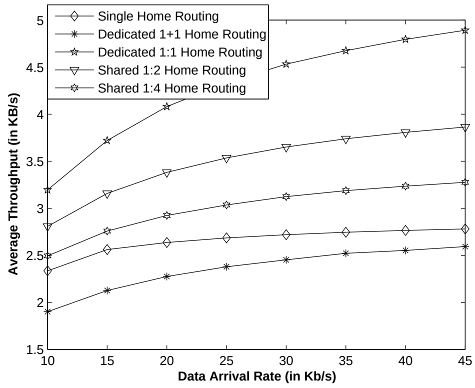


Fig. 7. Average throughput versus data arrival rate.

to SHR and 1:1 DHR. We can observe that the shared homing techniques, such as 1:2 and 1:4 result in intermediate average throughput for limited increase in network resources.

IV. Conclusion

In this paper, we presented two dedicated (1+1 and 1:1) and two shared (1:2 and 1:4) dual-homed fault-tolerant routing techniques for wireless sensor networks. Simulation results (without data fusion) show that 1:1 dedicated and 1:N shared DHR consistently outperforms SHR based on performance metrics, such as average end-to-end packet delay, average throughput, average packet loss probability, and network lifetime. 1+1 DHR minimizes the average loss probability compared to all other routing techniques, until the time of cluster-head failures. However, 1+1 DHR due to higher energy expenditure tends to decrease average throughput, average end-to-end delay, and network lifetime of network. Through extensive simulations, we have observed that 1:1 DHR offers up to 99.32% decrease in average loss probability and up to 36.82% increase in average throughput compared to SHR. 1:1 DHR delivers the best performance results at all data rates as compared to all the other policies. For networks with cost constraints, shared 1:2 DHR gives better performance with up to 20.25% increase in average throughput and up to 49.28% decrease in average loss probability as compared to SHR.

An important area for future work is the implementation grade-of-protection routing in multi-layer wireless sensor networks with data fusion [17]. In this paper, we assume that the node faults are permanent. If the faults are dynamic and intermittent, there are important design issues related to rerouting data back-and-forth between the primary home and the backup home.

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