Evaluation of Dual-Homed Fault-Tolerant Routing in Wireless Sensor Networks

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Abstract— **One of the most fundamental purposes 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 dependable wireless sensor network. Failure dependability relates to providing dependability against node and/or link failures. In multi-layered wireless sensor networks with data fusion, we observe that as the data propagates from the sensor node to the sink, the data packet represents an increasing number of sensor nodes (sub-tree) in the network. Hence, it is critical that this data packet reaches the sink, since the loss of a single packet eliminates the information sensed by a whole (possibly large) sub-tree of sensor nodes. We evaluate two dual-homed routing techniques for providing fault-tolerance, namely *1+1 dual-homing* and *1:1 dual homing*. Based on extensive simulation results, we observe that 1:1 dual-homed routing minimizes packet loss, increases network throughput, and increases network lifetime compared to the 1+1 dual-homed routing and the traditional single-homed routing techniques.**

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. These sensors consist of a microprocessor capable of handling a few million instructions per second, limited storage in the order of a few kilobyte of RAM, a short-range radio transmitter, a small power source (often a battery), and a couple of sensors and/or actuators to interact with the environment [1]. Such tiny sensor nodes that are deployed in an ad hoc fashion and that cooperate on sensing a physical phenomenon, have led to the emergence and deployment of wireless sensor networks. Sensor networks hold the promise of revolutionizing sensing in a wide range of application domains because of their reliability, accuracy, flexibility, cost-effectiveness, and ease of deployment. Sensor networks are envisioned to invade the world for data acquisition like the way the Internet has taken over the world for data dissemination.

A typical wireless sensor network, shown in Fig.1(a), consists of one or more sink nodes and many sensor nodes scattered across a sensing site. Each of these scattered sensor nodes is capable to collect the data and forward the data back to the sink through a multi-hop architecture. The data will be delivered to the user at the remote site through the Internet connection. A gateway usually resides between the sink and the Internet and provides the interface between them.

Data fusion and *multi-layered architecture* are essential energy efficient approaches to provide scalability for large-scale sensor networks. In the data fusion process, a data fusion node receives data from a number of sensors, conducts data fusion, and then sends the result (decision) to the base station. Many energy-aware routing protocols and algorithms have been proposed for data-centric network with data fusion, including SPIN [2], sequential assignment routing algorithm (SAR) [3], and directed diffusion [4].

Clustered or layered structures have been particularly appreciated in building large-scale sensor networks [5], [6], [7], [8], [9], [10]. The Low-Energy Adaptive Clustering Hierarchy (LEACH) [5] 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 using the routing information. 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 nodes' residual energy and a secondary parameter, such as node proximity to its neighbors or node degree [6]. The Robust Energy Efficient Distributed (REED) clustering algorithm achieves k-fault tolerance by selecting k independent sets of cluster-heads [7]. In [8], 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.

Typically large-scale wireless sensor networks that monitor a sensing field adopt the multi-layered architecture. These networks usually consists of different types of nodes such as sensor nodes, cluster-heads, and a base station node. The sensor nodes are responsible for collecting information about different parameters such as temperature, pressure, humidity, and luminescence. The cluster-heads are responsible for both sensing data as well as relaying the data received from the group (or the cluster) of sensor nodes on to the base station or to the next higher-layer cluster-head that is closer to the base station. The data transmission path may propagate through multiple layers before reaching the destination base station. In a layered heterogenous network, the cluster-heads are typically more capable than the sensor nodes. In order to minimize the energy spent on data transmission, the cluster-heads fuse the data sent from each sensor node within its cluster using suitable fusion functions such as minimum, maximum, and average. This aggregated information is now transmitted to the next higher-layer cluster-head as the data makes its way toward the base station. We can see that the flow of information in a sensor network follows the structure of a *tree*, wherein the *sensors* represent the *children*, the *cluster-heads* represent the *ancestors*, and the *base station* represents the *root* of the tree. In the multi-layered architecture, CDMA or FDMA are used

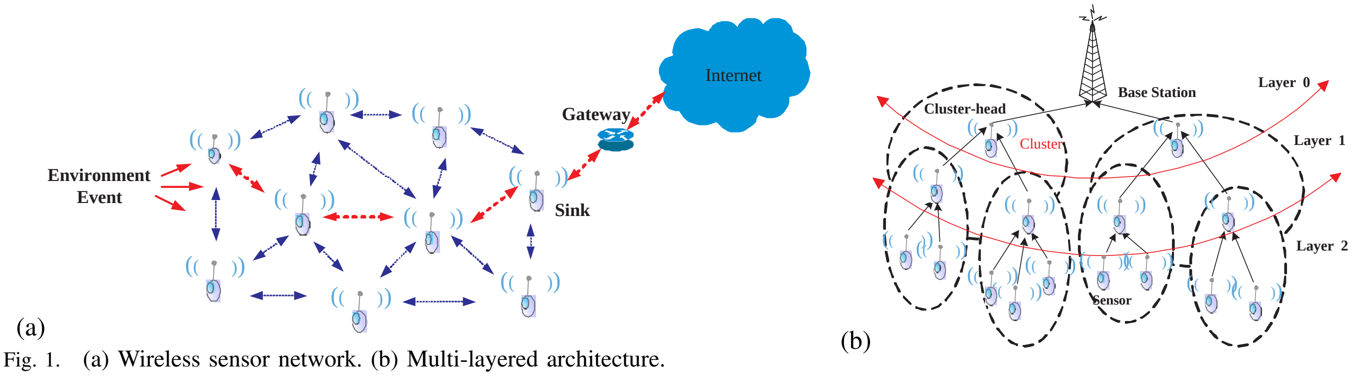

Fig. 1. (a) Wireless sensor network. (b) Multi-layered architecture.

for the communication among clusters and TDMA is used for the communication within the cluster.

In the multi-layered architecture, each cluster member (or outward node) has only one inward node as its cluster-head. If the inward cluster-head node fails, the data from the outward node will be lost until a new inward cluster-head is selected. In the multi-layered architecture, the loss caused by the inward cluster-head failure can be worse than the failure of an intermediate sensor node in a flat (single-layered) architecture. Consider a large-scale wireless sensor network as shown in Fig. 1(b) with thousands of sensor nodes organized into multiple layers. We observe that as the data propagates closer to the base station, the data packet represents an increasing number of senor nodes in the network. Hence, 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 sub-tree of sensor nodes.

The concept of dual-homing [11] is widely used in the Internet to provide fault-tolerance against node and/or link failures. Due to the inherent broadcast nature of data transmission in wireless networks, it is energy efficient to apply dual-homing techniques in wireless sensor networks since minimal extra transmission energy will be consumed.

In this paper, we evaluate dual-homing based fault-tolerant routing techniques for protection against network failures in wireless sensor networks. We thoroughly investigate the problem keeping sensor node's energy and network scalability in mind. Section II describes specific dual-homing based routing techniques for supporting fault-tolerance in dependable wireless sensor networks. Section III presents our simulation results and Section IV concludes the paper.

II. MULTI-HOMED FAULT-TOLERANT ROUTING

Due to the radio broadcast communication characteristic in the wireless sensor network and data fusion, it is energy efficient to apply multi-homed fault-tolerance techniques to protect against cluster-head failures. The following are some of the design principles that we need to consider when applying multi-homed fault-tolerant routing techniques in wireless sensor networks:

- Whether each cluster should have multiple dedicated higher-layer cluster-heads or a shared higher-level cluster-head.
- Whether data should be sent to multiple higher-layer cluster-heads simultaneously or data should only be sent to the primary higher-layer cluster-head and sent to the backup cluster-heads only if the primary cluster-head fails.
- Whether a higher-layer cluster-head should be aware of the multi-homing techniques in the lower-layer or not.

Based on the choices of the above design considerations, we can classify the multi-homed fault-tolerant routing techniques into dedicated 1:1 multi-homed routing, dedicated 1+1 multi-homed routing, shared multi-homed routing, coordinated multi-homed routing, and independent multi-homed routing. Without loss of the generality, in the remains of this section, we discuss different dual-homing fault tolerance techniques. These fault tolerance techniques can provide different levels of fault tolerance at different levels of cost. In this paper, we limit our discussion to dedicated 1+1 and 1:1 dual-homed routing techniques.

A. 1+1 Dual-Homed Routing

In a *1+1 Dual-Homed Routing* (DHR) technique, 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 (dual home). The primary cluster-head and the backup cluster-head uses the frequency (if FDMA is used) or the code (if CDMA is used) to receive the data and the time slot scheme for each sensor node in the cluster is the same for both primary cluster-head and the backup cluster-head. Fig. 2(a) demonstrates the principle working of 1+1 dual-homed fault-tolerant routing.

We can observe that 1+1 DHR technique can guarantee data loss subject to a single cluster-head failure. The primary issue of 1+1 DHR is that every data packet is duplicated and forwarded over the dual-paths on to the base station leading to increased energy consumption per packet transfer.

B. 1:1 Dual-Homed Routing

In a *1:1 Dual-Homed Routing* technique, 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 needs to notify the backup cluster-head with the frequency (if FDMA is used) or the code (if CDMA is used) it uses

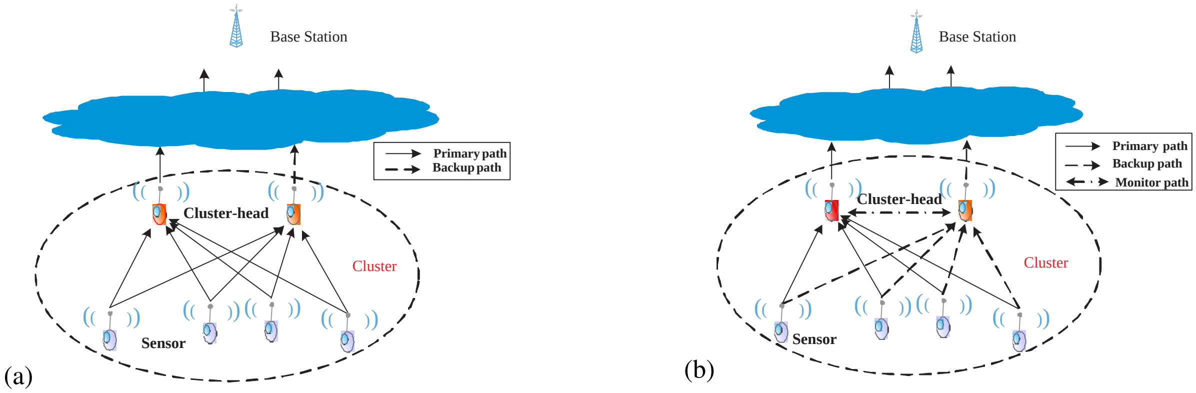

Fig. 2. (a) 1+1 dual-homed fault-tolerant routing and (b) 1:1 dual-homed fault-tolerant routing.

to receive the data from the cluster members. Meanwhile, the primary cluster-head also needs to notify the backup cluster-head with the TDMA schedule for each sensor in the cluster. When the primary cluster-head fails, the backup cluster-head will tune to the frequency or code on which the primary cluster-head used to receive data. All the data from the cluster will be shifted to the backup cluster-head. Fig. 2(b) demonstrates the principle working of 1:1 dual-homed fault-tolerant routing.

We can observe that 1:1 DHR technique is transparent to the source sensor nodes, since the sensor do not need to change their transmission frequency or code, or change their time slot 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 and the other is that the primary cluster-head should notify the backup cluster-head as to when it is about to deplete its energy (or fail). In either case, there might be some data loss during handover from the primary cluster-head to backup cluster-head.

III. SIMULATION RESULTS

In order to evaluate the performance of our proposed routing techniques, we run simulation on a 10-node multi-hop wireless sensor network depicted in Fig.3 In order to compare the proposed dual-homing techniques, we define a baseline technique, known as *single-homed* routing (SHR). SHR is the traditional single-path (single-home) routing technique that is not tolerant against node (or link) failure. In SHR, when the source sensor node (Node 0) transmits a packet, the packet is sensed only by single sensor node or single home (Node 3). Using Ad hoc On-demand Distance Vector (AODV) [12], [13] routing, the packet is routed to the base station (Node 10) via Route $3-5-8-10$. We observe that there exists a single non-fault tolerant path to forward data packets to the base station.

In 1+1 dual-homed routing, when the source sensor node (Node 0) transmits a packet, the packet is forwarded by two sensor nodes, namely the dual-homes Node 3 and Node 6. The two copies of the packet are simultaneously routed to the base station (Node 10) via the primary Route $3-5-8-10$ and the backup Route $6-9-10$. Redundant duplicate data packets are forwarded at the expense of increased energy consumption. Note that the end-to-end packet delay through the primary route (via Node 3) is larger then the backup route (via Node 6), since route with least energy consumption (not delay) is set to be the primary route.

In 1:1 dual-homed routing, when the source sensor node (Node 0) transmits a packet, the packet is forwarded only by the primary home, Node 3, which routes the packet to the base station using the primary Route $3-5-8-10$. Once, the primary home fails, the source node transmits packets through the backup home, Node 6 to the base station using the backup Route $6-9-10$. Thus at any particular time instant, there is a single route existing for forwarding the data packets.

A. *Simulation Model*

We use NS-2 [14] and NRL Sensorsim [15] discrete-event simulators to evaluate the performance of the proposed routing techniques. The following are the important simulation assumptions. Sensing field configuration is 450 m * 450 m with 10 sensor nodes and 1 base station. Transmission range is 250 m; data rate is 1 Mbps; packet length is 1000 bytes. The power levels are as follows: transmit power = 18.75 mW, receive power = 9.5 mW, sense power = 0.1 μW, and idle power = 0.0675 mW. We set the same transmit power, receive power and sense power for all nodes. We also set an initial energy of 10000 J for each node (except base station) in all our policies. Total number of packets simulated is 10^5. Sensor nodes route the packets to the base station using Ad hoc On-demand Distance Vector (AODV) routing protocol. Each sensor that routes packets is assumed to have a packet queue capable of holding 50 packets. We denote the inter-arrival time between two newly arriving sensor packets as the *pulse rate*, and we evaluate for the range 0.5-5.0 seconds.

B. *Performance Results*

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

- Network lifetime: time when the first packet is dropped due to route failure.
- Loss probability: ratio of number of data packets dropped to the number of data packets actually sent by a sensor node to the base station.

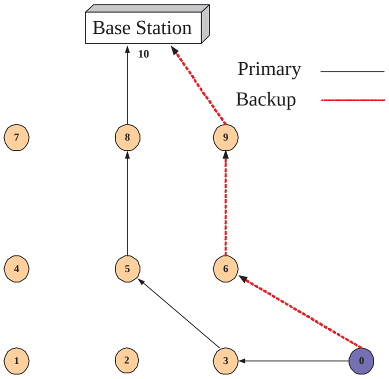

Fig. 3. 10-node grid network topology.

- End-to-end packet delay: the average time a packet takes from the source sensor node to the base station. Delays include queuing delay, propagation delay, and transmission delay.
- Throughput: number of data packets (that are sent from Node 0) successfully received at the base station per unit time.

In addition, average packet loss probability and average end-to-end packet delay are calculated over the entire period from the transmission of the first packet from the source node until the transmission of the last packet before the source node fails. While, on-line loss probability and On-line end-to-end packet delay are updated every time a packet is received at the base station.

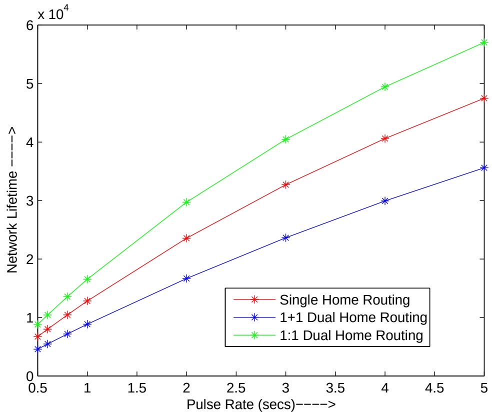

Fig. 4. Network lifetime versus pulse rate (packet inter-arrival time).

Figure 4 plots the network lifetime versus pulse rate for different routing techniques. We observe that 1:1 DHR outperforms to SHR and 1+1 DHR at all pulse rates. In 1+1 DHR, packets are routed simultaneously through both routes at all times and hence more energy is consumed for forwarding redundant data packets. Hence its network lifetime is the least as compared to all other scenarios. In SHR, packets are routed through a single primary route and the network dies after the primary home fails. In 1:1 DHR, data packets are routed through either primary or backup paths, hence the energy consumption will be much less than 1+1 DHR. Also, 1:1 DHR network continues to operate even after the primary home has failed, thereby increasing total network lifetime.

In our simulation, packet loss can be either due to sensor buffer overflow or due to sensor node failure. On closer introspection, we have observed that packet loss is primarily due to buffer overflow at low pulse rates (high loads). While at higher pulse rates (low loads) the packet loss is primarily due to node failures. Fig.5(a) shows the average packet loss probability versus pulse rate for the different routing techniques. At low pulse rates, SHR experiences higher loss as it is more prone to packet loss due to buffer overflows as compared to 1+1 DHR. Hence, SHR experiences higher average packet loss probability at lower pulse rates. As the pulse rate increases (load decreases), the packet loss is primarily due to node failures. We observe that 1+1 DHR consumes at least twice the amount of energy as compared to SHR and will experience node failures much earlier. Hence, 1+1 DHR experiences higher average packet loss probability at higher pulse rates (> 2.5 seconds). We also observe that 1:1 DHR has the best performance for all the pulse rates considered.

Figure 5(b) plots the on-line average packet loss versus time for different routing techniques with a pulse rate (packet inter-arrival time) of 3 seconds. At pulse rate of 3 seconds there is no loss due to sensor node's buffer overflow, since the arrival rate is low. We can clearly observe the exact time instance when the primary or backup homes fail and also the corresponding increase in the on-line packet loss probability of the different policies. We see that the primary node in SHR fails first, followed by the failure of both the homes in 1+1 DHR, and finally the failure of both the homes in 1:1 DHR. In SHR, the packets are always routed only through primary route and once a node on the route fails all data packets sent are lost until the simulation terminates. In 1+1 DHR, the packets are forwarded through both the primary and backup homes simultaneously; loss occurs only when both the primary and backup homes fail. In 1:1 DHR, the packets are initially forwarded through primary path until the primary home fails. After primary route fails, the remaining packets route through backup path until the network experiences another node failure, i.e., 1:1 DHR behaves like a SHR with single route for forwarding packets.

Figure 6(a) plots the average end-to-end packet delay versus pulse rate for different routing techniques. We observe that the average end-to-end delay is least in 1+1 DHR as compared to SHR and 1:1 DHR at all pulse rates. 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. In 1:1 DHR, initially data packets are routed through primary path (longer route with larger time delay). After primary home fails, packets are routed through backup (shorter route with smaller time delay) path, thus the average end-to-end packet delay will be less as compared to SHR where packets are routed only through the longer primary route.

Figure 6(b)-(d) plots the online average packet delays versus the pulse rate for different routing techniques at pulse rate of 3 seconds. We can observe that in single home network since the packets are always routed through primary path with higher time delay, the overall average online delay is higher as compared to all other networks. In 1+1 DHR, the packets are routed through both primary and backup paths. We consider

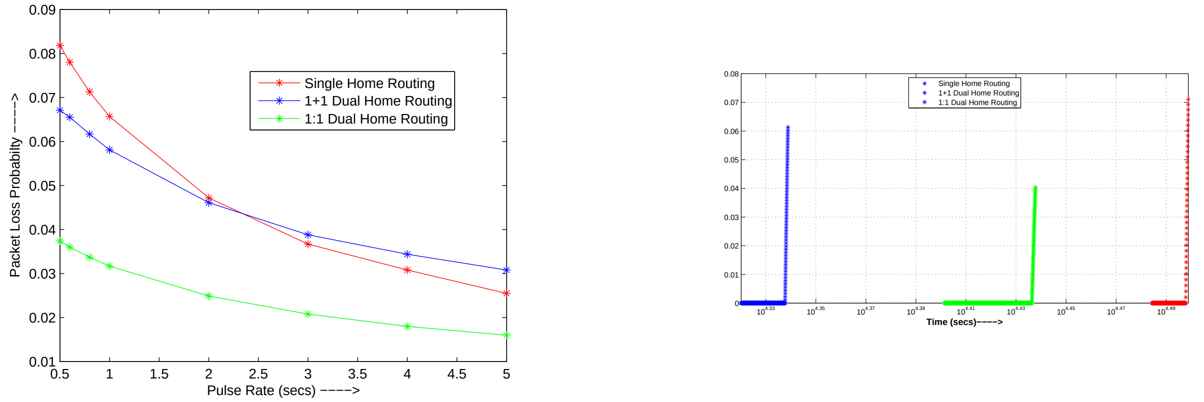

Fig. 5. (a) Average packet loss probability versus pulse rate. (b) On-line packet loss versus time with pulse rate of 3 seconds.

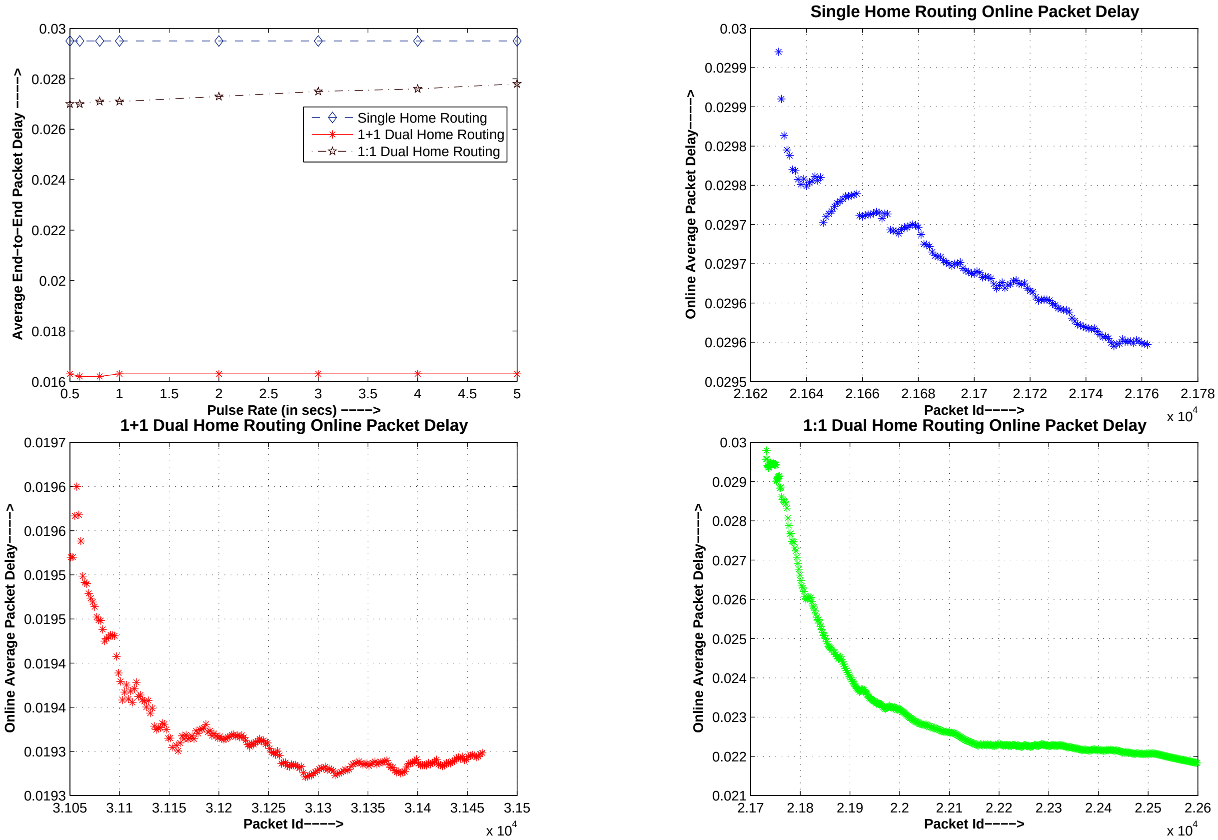

Fig. 6. (a) Average end-to-end packet delay versus pulse rate. On-line average packet delay versus time with pulse rate = 3 seconds for: (b) SHR, (c) 1+1 DHR, and (d) 1:1 DHR.

the route path with minimum time delay and thus packets route mostly via backup path. Hence the overall average online delay is the least in 1+1 DHR. In 1:1 DHR, the packets are routed initially through primary path and after the primary route fails they route through the backup path. Hence as we can observe initially the online average delay is larger until the primary route fails and then decreases gradually until the end of simulation. Thus, the overall online average online delay is intermediate between the other two routing networks.

Figure 7 plots the average throughput versus pulse rate for different routing techniques. We observe that 1:1 DHR performs better than both SHR and 1+1 DHR at all pulse rates. This is due to the fact that the overall energy consumption to route data packets is less in 1:1 DHR, and hence larger number of data packets is received by the base station until both route fails as compared to the other routing techniques. Thus, the average throughput will be greater than both SHR and 1+1 DHR. In 1+1 DHR, the number of successfully received packets is less until the end of network lifetime as compared to SHR as both the existing routes fail earlier due to increased energy consumption. Thus, the average throughput is least in 1+1 DHR as compared to SHR and 1:1 DHR.

IV. CONCLUSION

In this paper, we presented two dedicated dual-homed fault-tolerant routing techniques for wireless sensor networks. In 1+1 dual-homed routing, the data packets are routed through both primary and backup paths simultaneously whereas in 1:1

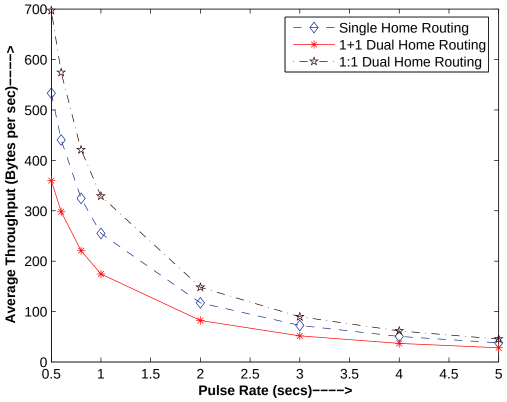

Fig. 7. Average throughput versus pulse rate.

dual-homed routing, the packets are routed through one of the two existing routes at any given time instant. Simulation results show that dedicated dual-homed routing consistently outperforms single-homed routing based on performance metrics, such as average end-to-end packet delay, average throughput, average packet loss probability and network lifetime. However, 1+1 dual-homed routing due to higher energy expenditure tends to decrease average throughput and network lifetime of network. In general, 1:1 dual-homing offers superior overall fault tolerant performance compared to 1+1 dual-homing and single-homed routing.

In this paper, we have considered only dedicated dual-homed routing techniques to achieve fault tolerance. An important area for future work is the implementation of shared dual-homed fault-tolerant routing. Also, investigation of the benefit of coordinated dual-homed fault-tolerant routing techniques over independent dual-homed fault-tolerant routing techniques is important.

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