HDMRP: An Efficient Fault-Tolerant Multipath Routing Protocol for Heterogeneous Wireless Sensor Networks

Abdelkrim Hadjidj, Abdelmadjid Bouabdallah, and Yacine Challal

Heudiasyc UMR CNRS 6599, University of Technology of Compiegne, France
{ahadjidj,bouabdal,ychallal}@utc.fr

Abstract. In wireless sensor networks, fault tolerance represents a key issue and a design goal of primary concern. Indeed, nodes in wireless sensor networks are prone to failures due to energy depletion or hostile environments. Multipath routing protocols are a category of solutions which enables the network to operate properly despite of faults. In this paper, we present a new multipath routing protocol which provides strong fault tolerance by increasing the number of constructed paths up to three times in some scenarios. Our protocol relies on a new multipath construction paradigm that we have defined specifically for heterogeneous WSN. We call this paradigm: energy-node-disjointness. Our approach leverages a reasonable increase in the cost of the network to a longer network lifetime and a higher resilience and fault tolerance.

Keywords: Fault Tolerance, Multipath Routing, Heterogeneous Wireless Sensor Networks.

1 Introduction

Recent advances in wireless communications and Micro-Electro-Mechanical systems have enabled the development of wireless sensor networks (WSN) which consist of many sensor nodes with sensing, computing and communication capabilities [1]. WSN are deployed over an area to periodically sense and monitor physical or environmental conditions and transmit the sensed data back to a base station. WSN have broad spectrum applications such as environment monitoring, target tracking, military surveillance and healthcare applications.

Heterogeneous WSNs (HWSN) are networks in which nodes have moderated capabilities and some powerful nodes, called masters, contribute to increase the network reliability, lifetime or the delivery ratio [24][11]. WSN Heterogeneity can have several forms: In *Energy Heterogeneity* case, the network is composed of battery-powered sensor nodes and some line-powered master nodes with no energy constraints. Master nodes can also be equipped with ambient energy harvesting technology for incessantly power supplying [21]. In *Link Heterogeneity* case, master nodes have different radio-transceivers in term of distance and bandwidth. This heterogeneity is commonplace in tiered WSN [6][2] where

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cluster-heads have different radio-transceivers for inter-cluster communications and intra-cluster communications. In *Hardware Heterogeneity* case, nodes have different set of sensors and can sense different parameters. This has the benefits of keeping mote's cost relatively low since a node will not need a full sensor set[21]. Finally, in *Security Heterogeneity* case, master nodes are equipped with tamper resistant devices or physical protection.

Due to battery depletion or hostile environments (e.g. wind, rain or high temperature) in which WSN may be deployed, sensor nodes are prone to failure. A part of the network can be disconnected and critical data maybe lost because of faults. Consequently, fault tolerance is a major concern in wireless sensor networks in general and even more in critical applications such as healthcare, forest firefighting or nuclear radiation detection where it is not acceptable to lose sensitive data. Fault tolerance is the capacity to keep a network working correctly despite of failures. Multipath routing protocols are a category of fault tolerance techniques which provides tolerance of faults and increase the network resilience since the probability that all constructed paths fall at the same time because of the same fault is mitigated. If we construct k disjoint paths, we can guarantee that a node remains connected to the Sink even after the failure of up to k-1 paths. Consequently, increasing the number of discovered disjoint paths will improve the fault tolerance of the network. *Node-disjoint multipath routing protocols* [5] construct paths with no common nodes/links. This leads to strong fault tolerance since a node failure impacts only one path. However, node-disjoint routing protocols induce large control message overhead and a lack of scalability. *Braided multipath routing protocols* [5] construct paths with possibly common nodes or links to avoid control messages overhead but provide slightest fault tolerance. Indeed, a failure of a node belonging to several paths will cause the failure of all those paths and may disconnect a large part of the network.

In this paper, we propose a new fault tolerant multipath routing protocol for heterogeneous wireless sensor networks. Simulation results show that our protocol is able to discover up to three times more node disjoint paths compared to existing protocols and improves the fault tolerance by 30% when node failure rate is less than 30%. While most of multipath routing protocols deal with homogenous wireless sensor networks, our protocol HDMRP (Heterogeneous Disjoint Multipath Routing Protocol) is designed especially for HWSN and implements mechanisms to exploit and benefit from robustness and abundant resources in master nodes to significantly increase the network resilience and lifetime.

The rest of the paper is organized as follows. Section 2 gives an overview of existing multipath routing protocols. Section 3 describes the proposed routing protocol. Section 4 discusses the performance evaluation of the proposed routing protocol. Finally, section 5 concludes the paper.

2 Related Works

There has been a host of research works on multipath routing protocols for wireless sensor networks in the last few years. Multipath routing protocols are used for reliability [25][4],load balancing [15][10], QoS provisioning [4][12][22][3][9] and secure communications [19]. In this work, we are mainly interested in fault tolerant multipath routing construction. However, exploitation of these constructed multipath routes is out of the scope of this work.

In [13], Li et al. propose a Node-Disjoint Parallel Multipath Routing (DPMR) which uses one-hop response after a delay time at each node to construct multiple paths simultaneously. To ensure node-disjointness, only nodes that have not been used by other paths forward route requests to their neighbors. In [7], Hou and Shi present LAND, a Localized Algorithm for finding node disjoint paths which constructs a set of minimum cost node-disjoint paths from every node to the Sink. In [15], Lu et al. propose Energy-Efficient Multipath Routing Protocol (EEMRP), a node-disjoint multipath protocol which considers energy and hop count while constructing the multiple paths. EEMRP achieves high energy efficiency without considering network reliability. In [14], Lou and Kwon propose Branch routing protocol (BRP) to improve WSN reliability and security. BRP constructs several trees routed at sink's neighbors which represent branches on the network graph. Each node belongs to one and only one branch but can send data back to the sink on every branch it is aware about. The main drawback of this method is the limited number of discovered paths and therefore the limited fault tolerance.

Node-disjoint multipath routing protocols construct paths with no common nodes/links and provide high resilience and fault tolerance since a node failure impacts only one path. However, they usually suffer from control message overhead and a lack of scalability. Some researchers aim to reduce node-disjoint protocols overhead by relaxing the disjointness requirement. In [5], Ganesan et al. study disjoint and braided paths by comparing their performances and show that braided path protocols overhead is only half the overhead induced by node disjoint protocols. However, braided paths are weaker since a single node failure may cause the failure of multiple routes to the sink. In [23], Yang et al. present NC-RMR, a routing protocol for network reliability which constructs disjoint and braided multipath and uses network coding mechanism to reduce packet redundancy when using multipath delivery. In [16], Nasser et al. propose SEEM protocol (Secure and Energy-Efficient Multipath routing protocol) which finds both braided and disjoint paths and adopt a Client/Server scheme where the Sink (server) executes the paths discovery, paths selection and paths maintenance in a centralized way. As in link-state routing protocols [8], each node in SEEM sends its neighbors list to the sink which consumes so much energy and induces significant overhead.

In [18], Sohrabi et al. propose SAR algorithm (Sequential Assignment Routing) which considers the fact that nodes near the Sink relay more packets and actively participate in communications. As a result, they expend more energy and are more prone to failures due to quick battery depletion. Therefore, SAR requires disjointness only where it has the highest impact (one hop sink neighborhood). In [17], Ouadjaout et al. propose the SMRP protocol which introduces the assumption that Sink's neighbors are powerful master nodes. Therefore, SMRP requires disjointness after two hops sink's neighbors rather than one hop sink's neighbors. As a result, the number of discovered disjoint paths is increased but still limited.

Existing multipath routing protocols balance the tradeoff between fault-tolerance and communication overhead. Indeed, increasing the number of paths for a better fault-tolerance requires more messages exchange and communication overhead. In this paper, we present a new multipath routing protocol able to construct up to three times more multiple paths comparatively to existing protocols by using only one message per node. Furthermore, all above described protocols deal with homogeneous wireless sensor networks and do not consider the power of master nodes. Our protocol is designed especially for heterogeneous WSN and uses abundant resource in powerful master nodes to improve the network fault tolerance.

3 Heterogeneous Disjoint Multipath Routing Protocol (HDMRP)

In this section, we present our new efficient solution which provides fault tolerance in wireless sensor networks. First, we will introduce a new paradigm for heterogeneous wireless sensor networks: energy-node-disjoint paths. Next, we will describe our Heterogeneous Disjoint Multipath Routing Protocol which constructs multiple paths between the sink and each node in the network. Wireless sensor networks (WSN) are typically employed for monitoring and require data collection at a specific node called Sink. We consider a many-to-one traffic pattern where source sensors send measurement data to the Sink. As in several literature works and real-world wireless sensor networks implementations [21][6][20][2], we assume the existence of few robust powerful master nodes in the network.

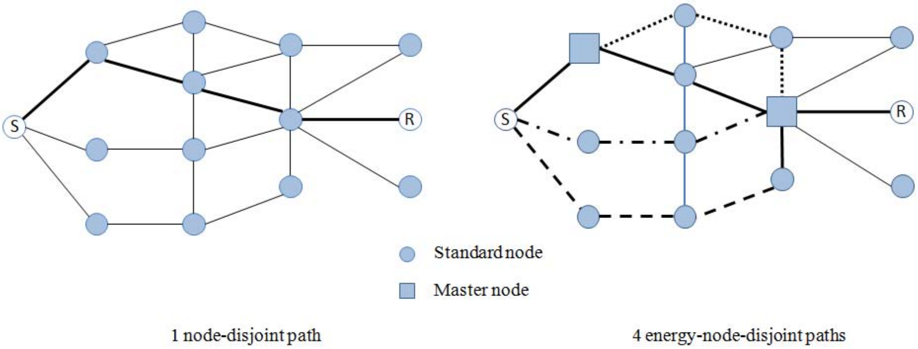

Fig. 1. Node-Disjoint paths and Energy-Node-Disjoint paths

3.1 Energy-Node-Disjointness

In heterogeneous wireless sensor networks, Master nodes are powerful nodes with mitigated energy constraints and able to ensure relatively high connectivity degree and hence relay data on several paths. For this reason, we have introduced a new energy-node-disjointness paradigm as follows:

Definition 1. *n paths are said energy-node-disjoint iff they have no common nodes or all their common nodes are master nodes*

So far, only node-disjointness has been used to build multipath routing topologies:

Definition 2. *n paths are said node-disjoint iff they have no common nodes*

Master nodes are powerful nodes and cannot suffer from battery depletion which is the most frequent node failure cause in WSN. In the case where a master node is common to several paths, the probability that it fails and impacts all paths to which it belongs is mitigated. Consequently, we have introduced a controlled intersection between paths at master nodes which will increase the number of discovered paths. Our protocol builds energy-node-disjoint paths in order to increases the number of alternative paths and therefore the network fault tolerance. For instance, our algorithm discovers four energy-node-disjoint paths between nodes S and D, instead of one node-disjoint path in the network of Fig. 1.

3.2 Protocol Description

In HDMRP, sink neighbors' are called root nodes and root neighbors are called sub-roots. The protocol uses Route REQuest (RREQ) message propagation through nodes to construct multiple energy-node-disjoint paths between each node and the sink. Each non root node maintains a routing table containing an entry for each discovered path. A RREQ corresponds to a path and has the following format: $\{R, S, P_{id}, len, Nmas\}$ where:

- R is the current round number
- S is the sending node id
- P_{id} is the path id
- len is the path length
- $Nmas$ is the number of master nodes in the path

During paths construction, a node may receive several RREQ messages corresponding to one or several paths. To guaranty node disjointness, each node forwards only one RREQ message to its neighbors and acts as a reducing element. However, Master nodes are powerful nodes able to ensure relatively high connectivity degree and can relay data on several paths. Instead of using all nodes as reducing elements belonging to only one path, HDMRP introduces a controlled intersection at master nodes by allowing them to forward several RREQ messages to their neighbors.

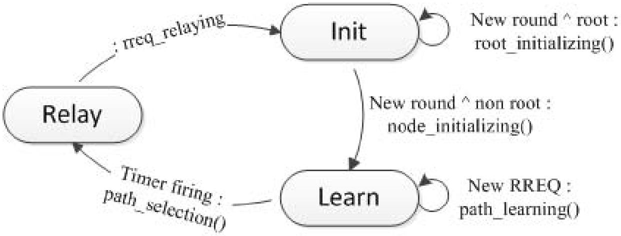

Fig. 2. HDMRP state chart

The Sink starts a new paths construction by broadcasting a route request message RREQ indicating a new round $RREQ.R$. Fig. 2 describes the evolution of a node state in the routing construction process. An arc between two states S_i and S_j has a label "$E : P$". This label means that when the node is in the state S_i and the event E occurs, the node executes the procedure P and passes to the state S_j. The description of the different procedures that a node must execute in each case is as follows:

root_initializing(): Upon receiving a RREQ indicating a new round $RREQ.R$, a root node relays it to its neighbors and waits for the next round. This terminates the current round construction phase for the root node. The node deduces that it is a root if the received RREQ has a S field equal to the sink ID (cf. Listing 1).

node_initializing(): Upon receiving a RREQ indicating a new round $RREQ.R$, a non root node in the *Init* state removes all previously discovered paths, adds the new received path to its routing table, sets a timer with a length enough sufficient for receiving several RREQs from the network and passes to new routes learning state (*learn state* in Fig. 2). In addition, if the node is a sub-root, it generates a new tagged RREQ by putting its ID in the P_{id} field and broadcasts it to its neighborhood. A node deduces that it is a sub-root if it receives a RREQ message with an empty P_{id} field. See Listing 1, new round initialization part.

path_learning(): Upon receiving a tagged RREQ, a node adds it to its routing table if there's no entry with the same P_{id}. Otherwise, it chooses between the new received RREQ and the one in its routing table based on a cost function. See Listing 1, path learning part. For achieving high energy efficiency, we developed a cost function which ensures having the maximum number of master nodes in each path:

$$cost(RREQ) = \frac{RREQ.len}{RREQ.Nmas} \tag{1}$$

path_selection(): As illustrated in the timer handler of Listing 1, when the timer fires the node has to select one or several RREQs to relay and passes to the *Relay* state. In the case where the node is a master node, it selects all the RREQs stored in its routing table in P2. This increases the connectivity degree of master nodes and hence the number of energy-node-disjoint paths. In the other case, ordinary nodes select one RREQ among those stored in the routing table in P2. This ensures the node-disjointness of paths and hence increases resiliency.

rreq_relaying(): In the *Relay* state, each node broadcasts to its neighbors the selected RREQs and passes to the init state. This terminates the current round construction phase for the node.

Listing 1. HDMRP Algorithm

```
state = init;
RREQ_Processing()
{
newRREQ = receive();
if(currentRound < newRREQ.R)
{
    /* new round initialization */
    currentRound = newRREQ.R
    if(newRREQ.S == 0)
    {
        /* root node */
        newRREQ.S = getNodeID();
        newRREQ.len ++;
        send(newRREQ);
    }
    else
    {
        flush(received_RREQs);
        received_RREQs.add(newRREQ);
        start_timer();
        if(newRREQ.pid == null)
        {
            /* subroot node */
            newRREQ.pid = getNodeID();
            newRREQ.S = getNodeID();
            newRREQ.len ++;
            send(newRREQ);
        }
        state = learn;
    }
}
else if(state == learn && currentRound == newRREQ.rid)
     /* path learning */
     if(cost(newRREQ)<currentCost(newRREQ.pid))
        received_RREQs.add(newRREQ);
}
Timer_Handler()
{
    /* path selection */
    if(nodeIsMaster())
        selected_RREQs = received_RREQs;
    else
    {
        i = random(received_RREQs.size())
        selected_RREQs = received_RREQs[i];
    }
    for (i=0; i<selected_RREQs.size(); i++)
        send(selected_RREQs[i]);
    state = init;
}
```

4 Numerical Results

We have evaluated the performance of our protocol HDMRP by conducting intensive simulations with different protocols and different scenarios. We report the performance results in what follows.

4.1 Simulation Model

We have implemented HDMRP protocol using *networkx*, a graph library for python. To estimate the impact of introducing powerful master nodes to the network, we have considered three variants with different master nodes densities : 5%, 10% and 20%. In addition to our protocol, we have implemented BRP and SMRP protocols which we previously introduced. BRP and SMRP are the only node disjoint protocols which, like HDMRP, use only one message per node in the multipath construction.

The number of constructed paths between a node and the Sink is an important metric to estimate the fault tolerance of our solution. The higher the number of constructed paths, the better the fault tolerance is. For each protocol and each scenario, we measured the average number of discovered paths per node (Y axis) depending on the number of nodes in the network (X axis). For each network size, we have generated 100 random network topologies and calculated the average number of discovered paths over this 100 iterations. The network topology generation parameters are as follows: (i) the network area size is 50 X 50 units, (ii) the Sink node is located in the center of the network, (iii) each node has a communication range of 2 units, (iv) nodes and master nodes are randomly distributed over the network area.

4.2 Number of Paths

Fig. 3 illustrates the average number of discovered paths between a node and the Sink depending on the network size. We notice that in the three variants, our protocol computes more paths than BRP and SMRP. HDMRP constructs up to 110% more paths than BRP and SMRP when 20% of nodes are masters. Furthermore, this performance increase can achieve 35% when only 5% of nodes are master nodes. These results match our expectations: our protocol discovers more paths than BRP and SMRP when master nodes are present. Therefore, it achieves a higher fault tolerance. The difference between HDMRP and the other protocols becomes visible only when the network size is greater than 400 nodes. This can be explained by the limited node density in the case of small networks. Indeed, the probability that a master node receives and relays multiple RREQs is small when the network density is low.

4.3 Master Nodes Deployment Strategy

Master nodes placement strategy is an important factor in HDMRP since the protocol performance is significantly affected by the master nodes position.

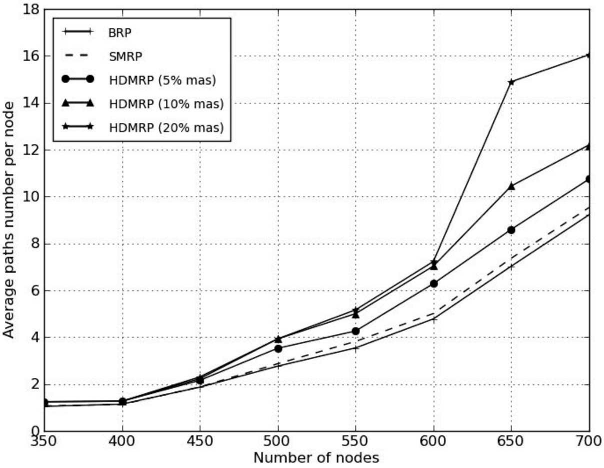

Fig. 3. Average paths number when master nodes are randomly distributed over the network area

To demonstrate this property, we have conducted simulations to compare between three master nodes deployment strategies : Randomized master nodes distribution, alternated level distribution and concentrated area coverage. In randomized distribution, master nodes are deployed uniformly through the whole network area. In alternated level distribution, we place master nodes in even levels and standard nodes in odd levels. This ensures that a node near the sink will be between at least two master nodes. In concentrated area coverage, all master nodes are randomly deployed around the Sink.

Fig. 4 and Fig. 6 illustrates the average number of discovered paths between a node and the Sink depending on network size and the master nodes deployment strategy. Fig. 4 compares between the number of constructed paths in the case of alternated level distribution and the case of randomized distribution. We notice that the number of constructed paths in the alternated level distribution is the highest in every scenario. The results match our expectations and confirm that master nodes deployment strategy has an impact on HDMRP performance. Fig. 5 illustrates the improvement rate of the alternated level deployment strategy comparatively to randomized distribution. We remark an improvement between 5% and 20% in the number of constructed paths when using alternated level deployment strategy. This high improvement rate can be explained by the continuous intensive propagation of tags due to the presence of master nodes every two hops.

To go further, we have compared between the number of constructed paths in the case of concentrated area coverage and the case of randomized distribution. The improvement of the concentrated deployment can be clearly seen in Fig. 6 where the number of discovered paths is always the highest in concentrated deployment case. An interesting observation is that the number of constructed paths when only 5% of nodes are master nodes in the concentrated deployment is almost the same when 20% of nodes are master nodes in randomized distribution. Consequently, with a proper master nodes distribution, HDMRP constructs up to 110% more paths than BRP and SMRP when only 5% of nodes are master nodes. Fig. 7 illustrates the improvement rates of the concentrated area coverage strategy comparatively to randomized distribution. We remark an improvement up to 34% in the number of constructed path when using concentrated area coverage deployment strategy. This can be explained by the fact that masters far from the Sink and situated in the network border have no impact on the number of discovered paths. Indeed, concentrating these master nodes near the sink enable our protocol to achieve very high performance.

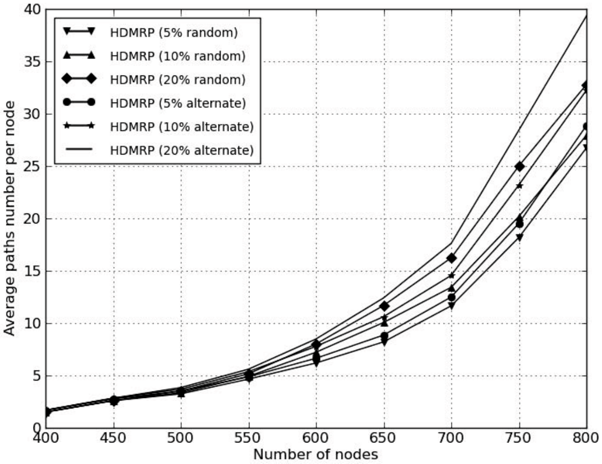

Fig. 4. Average paths number when master nodes are in alternate levels

4.4 Fault Tolerance

To evaluate the fault tolerance of HDMRP, we have considered the impact of node failure on the network connectivity. We have first run BRP, SMRP and HDMRP protocols to construct multiple paths on different network topologies. Then we have varied the node failure rate from 5% to 30% and computed the number of nodes that still have a functional path to the sink (connected nodes). For each protocol, we have executed 100 simulations to estimate the average connected nodes rate (Y axis) depending on node failure rate (X axis). Simulation parameters are as follows: (i) failures are randomly distributed on network nodes (ii) master nodes have the same failure probability as nodes (iii) HDMRP is used with 10% of randomly deployed master nodes.

Fig. 8 illustrates the average number of connected nodes depending on nodes failure rate. We notice that compared to BRP and SMRP, HDMRP is more fault tolerant. For instance, when 10% of nodes fail, 88% of nodes stay connected in HDMRP and only 70% of nodes stay connected in BRP and SMRP. This

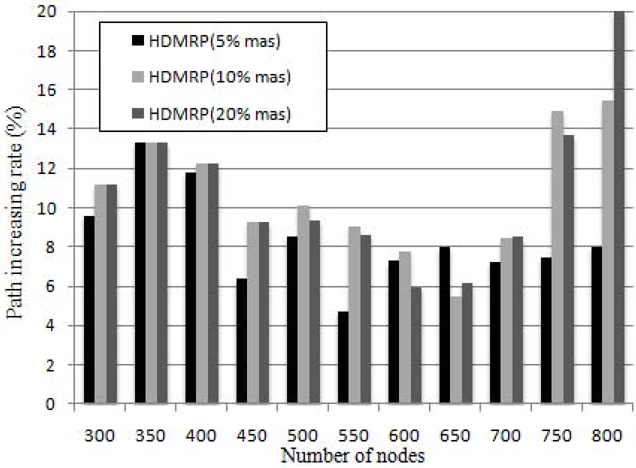

Fig. 5. Increase rate in the number of discovered path in alternate levels deployment strategy

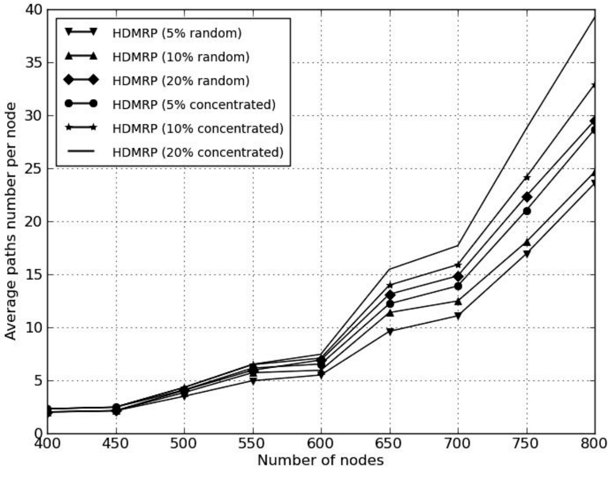

Fig. 6. Average paths number when master nodes are deployed around the sink

is because HDMRP constructs more energy-node-disjoint paths between each node and the sink. Consequently, each node has several alternative paths to the sink in presence of failures. Fig.8 shows that connected nodes ratio in HDMRP is above 80% for node failure rate of up to 17%. Furthermore, the number of connected nodes is almost the same as the number of working nodes for node failure rate of up to 20%. This demonstrates that node failures have a mitigated impact on working nodes and the network. Consequently, HDMRP shows very high robustness and fault tolerance even when the quarter of nodes fail.

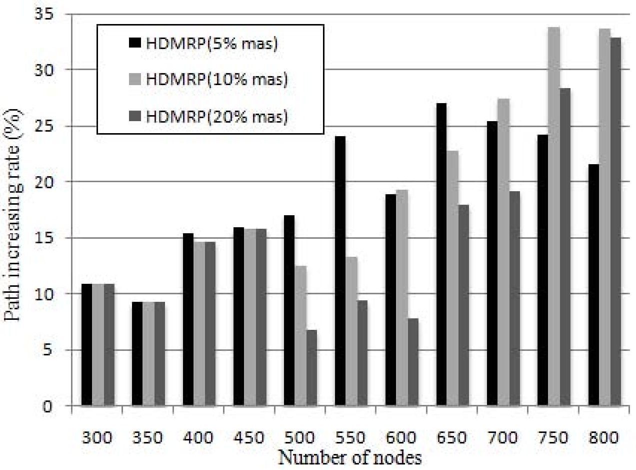

Fig. 7. Increase rate in the number of discovered path in concentrated deployment strategy

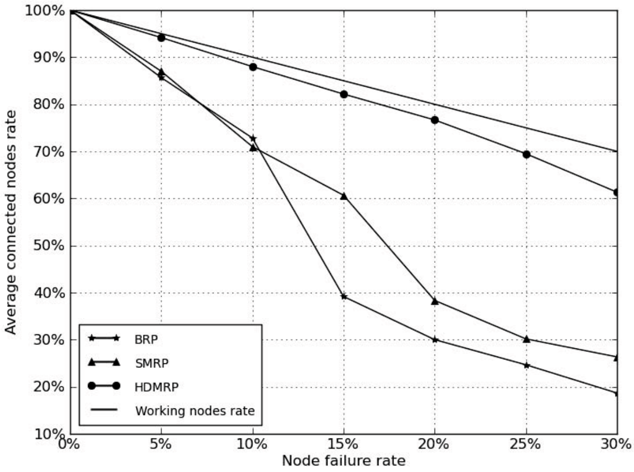

Fig. 8. Average connected nodes rate when network size is 600

5 Conclusion

In this paper, we deal with the challenging issue of providing fault tolerance in wireless sensor networks. We first define a new multipath paradigm for heterogeneous wireless sensor networks. Then, we propose a new fault tolerant multipath routing protocol which discovers an important number of energy node disjoint paths with the slightest overhead of one message per node. We conduct intensive simulations to evaluate our protocol with different scenarios, master nodes densities and deployment strategies. Simulation results are very encouraging and demonstrate the high performance and fault tolerance of our proposed protocol.

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