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Energy efficient fault-tolerant multipath routing scheme for wireless sensor networks

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Abstract

In wireless sensor network (MSN), reliability is the main issue to design any routing technique. To design a comprehensive reliable wireless sensor network, it is essential to consider node failure and energy constrain as inevitable phenomena. In this paper we present energy efficient node fault diagnosis and recovery for wireless sensor networks referred as energy efficient fault tolerant multipath routing scheme for wireless sensor network. The scheme is based on multipath data routing. One shortest path is used for main data routing in our scheme and other two backup paths are used as alternative path for faulty network and to handle the overloaded traffic on main channel. Shortest pat data routing ensures energy efficient data routing. Extensive simulation results have revealed that the performance of the proposed scheme is energy efficient and can tolerates more than 60% of fault.

Keywords WSN, fault tolerance (FT), load balance, routing, energy efficiency

1 Introduction

WSN is a collection of hundreds and thousands of low cost, low power smart sensing devices. Sensor nodes are deployed in a monitoring area. They collect data from monitoring environment and transmit to base station (BS) by multi-hope or single hope communication. In WSN, fault occurrence probability is very high compared to traditional networking [1]. On the other hand, networks maintenance and nodes replacement is impossible due to remote deployment. These features motivate researchers to make automatic fault management techniques for wireless sensor networks. As a result now a day's different types fault detection and FT technique have been proposed [2–3]. Kim M, et al. proposed a multipath fault tolerant routing protocol based on the load balancing in 2008 [4]. In this paper, authors diagnose node failures along any individual path and increase the network persistence. The protocol constructs path between different nodes. Li et al. proposed a node-disjoint parallel multipath routing algorithm in 2005 [5]. This technique uses source delay and one hop response mechanism to construct multiple paths concurrently. In 2010 Yang et al. [6] proposed a network coding base reliable disjoint and braided multipath routing. In this technique the authors construct disjoint and braided multipath to increase the network reliability. It also uses network coding mechanism to reduce packet redundancy when using multipath delivery. Challal et al. proposed secure multipath fault tolerance technique known as SMRP/SEIF in 2011 [7]. In this technique introduce fault tolerant routing scheme with a high level of reliability through a secure multipath communication topology. Occurrences of fault in wireless sensor network are broadly classified in two groups; transmission fault and node fault. The node fault [8–10] is further classified into five groups. These are power fault, sensor circuit fault, microcontroller fault, transmitter circuit fault and receive circuit fault as discussed in Ref. [11]. Energy efficiency is a prime metric in WSN performance analysis. This motivates us to propose an algorithm for fault tolerant and energy efficient routing.

In this paper, we propose a fault tolerant routing which involves fault recovery process with fault detection scheme,

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referred to as energy efficient fault tolerant multipath routing scheme for wireless sensor network (EEFTMR). In EEFTMR technique every sensor node transmits its data to BS through shortest path. If data and node fault occurs in the network, these are recovered very fast and data are transmitted to BS with minimum time and energy loss. The EEFTMR also controls the data traffic when data are transmitted to cluster head (CH) or BS.

The rest of this paper is organized as follows. Sect. 2 describe proposed load balanced model. In Sect. 3, we propose architecture for EEFTMR. The proposed methodology for EEFTMR is discussed in Sect. 4. Performances and comparison result are showed in Sect. 5. Finally, the paper is concluded in Sect. 6.

2 Load balancing mechanism in EEFTMR

In EEFTMR technique, we use standard data communication model originally proposed in Ref. [12]. In EEFTMR technique cluster size are calculated with the help of Theorem 1 and Theorem 2. Theorems 1 establishes a relation between number of message passing through a node and nodes energy. Theorem 2 establish a relation between numbers of nodes connection of a particular node with number of message passing in a particular time. The load of a node is directly affected by the number of node connected to a particular node. If number of node connection is increased then load on that particular node is increased. On the other hand, if number of connection is decreased then load of the particular node is decreased. Similarly, if load of a node is increased then energy loss of the sensor node is increased, if load of the sensor node is decreased then sensor node energy loss is decreased.

Definition 1 The load P_j of a node is depending on number of data packet receives and transmits by a particular node. The data load on a particular node is depended on number of sensor nodes connected with it and amount of data sensed by this particular node. If any node receives S_p data packet from a single connection and transmits data packet S_d through a single connection then P_j represents by the following equation.

$$P_j = \sum_{i=0}^{n} S_\mathrm{p} + S_\mathrm{d}$$

Theorem 1 If initial energy of a sensor node is U, then partial derivative of the total energy of a sensor node expressed in terms of number of message passing Δ_j at node j is equal to the load P_j at sensor node j. This theorem expressed symbolically as

$$\frac{\partial U}{\partial \Delta_j} = P_j$$

Proof Consider a series of loads $P_1, P_2, P_3, \ldots .P_j, \ldots P_n$ are acting on node 1, 2,..., j,..., n , are producing number of message $\varDelta_1, \varDelta_2, \ldots .\varDelta_j, \ldots \varDelta_n$. Now impose a small increment $\partial\varDelta_j$ to the message passing at the node j keeping all other load unchanged. As a consequence, the increments in the loads are $\partial P_1, \partial P_2, \ldots, \partial P_j, \ldots, \partial P_n$. The increment in the number of message at node j and consequent increments in loads at all the neighbour nodes. Therefore, $P_j \partial\varDelta_j = \varDelta_1 \partial P_1 + \varDelta_2 \partial P_2 + \ldots + \varDelta_j \partial P_j + \ldots . + \varDelta_n \partial P_n$, $\partial U / \partial\varDelta_j = P_j$ In the limit $\partial\varDelta_j \to 0$, the above equation becomes $\partial U / \partial\varDelta_j = P_j$.

Theorem 2 Partial derivative of the energy loss in sensor nodes expressed in terms of load with respect to any load P_j at any sensor nodes j is equal to the number of message passing $\varDelta_j$ through the jth node. This theorem may be expressed symbolically as $\partial U / \partial P_j = \varDelta_j$

Proof Consider a series of loads $P_1, P_2, P_3, \ldots, P_j, \ldots, P_n$ acting on a node j and for this section the message passed are $\varDelta_1, \varDelta_2, \ldots, \varDelta_j, \ldots, \varDelta_n$. Now impose a small increment ∂P_j to the load at the node j keeping all other factors unchanged. As a consequence, the message passing increases by $\partial\varDelta_1, \partial\varDelta_2, \ldots, \partial\varDelta_j, \ldots, \partial\varDelta_n$. However, due to increments in the load at node j, there is a consequent increment in message passing in all the neighbouring nodes. Therefore, $\varDelta_j \partial P_j = \Delta_1 \partial\varDelta_1 + \varDelta_2 \partial\varDelta_2 + \ldots + \varDelta_j \partial\varDelta_j + \ldots + \varDelta_n \partial\varDelta_n$, $\partial U / \partial P_j = \varDelta_j$ In the limit $\partial P_j \to 0$, the above equation becomes $\partial U / \partial P_j = \varDelta_j$.

3 Energy efficient fault tolerant multipath routing architecture

In EEFTMR technique, cluster size is calculated based on the CH load using Theorem 1 and Theorem 2. The CH load depends on the number of message received in cluster head and number of data transmitted from CH.

3.1 Fault tolerance data routing model

In EEFTMR technique sensor nodes are arranged into small clusters. Every cluster contains CH and cluster member nodes. Every cluster member node is capable of sending data over multiple paths. Cluster member nodes send their data in a shortest path to CH. Other paths are used for duplicated data transmission. Within a cluster a cluster member node sends its data to other cluster member nodes through three alternative paths. One of them is shortest, which is responsible for fast data transmission to CH. However, due to any external or internal problem shortest path fails, and then next available shortest alternative path is used to recover the faulty data transmission.

In EEFTMR technique, when data are reaching to the neighbouring destination node via data routing path, they first check their received data and their own sensed data. If these two are same then neighbour nodes are not forwarding the received data to others. If a node receives different data then receiver node sends receiving data toward the CH with shortest path.

In EEFTMR technique, clusters head and BS are also connected to each other with the help of multiple data path. The shortest path is mainly used for fast energy efficient data routing towards BS. Other two backup paths are used for duplicate data routing, which makes the network path fault tolerant.

3.2 Fault detection in EEFTMR

In EEFTMR technique when a data is received by the destination node, they compare the received data with its own sensed data. If the compared value is less than the threshold value, then the sensor circuit of the node is good. If a sensor node receives data from neighbour nodes, then the sensor node receiver circuit is considered as good. If a sensor node has not received any data from its neighbour nodes for a long period of time then they send a message to other neighbour nodes to check the health of the neighbours. If all the neighbour nodes reply, then the sending node consider that there is some transmission fault occurring between communicating neighbours. However, if any neighbour node does not respond then the node confirm that its receiver circuit is faulty. On the other hand if a communication node is not responding then it will be declared as dead node and that has been informed to all the neighbouring nodes.

3.3 Fault recovery in EEFTMR

Depending on the hardware condition of the node they are categorize as: normal node, traffic node, end node, dead node (Table 1) [11]. The categorization helps improving the network lifetime and decreases the percentage of dead node in the network. Detail fault recovery method is described in next section.

Table 1 Categorization of nodes with respect to different hardware circuit failure

Node category	Microcontroller	Sensor circuit	Transmitter circuit	Receiver circuit	Battery/ Power
Normal node	Non faulty	Non faulty	Non faulty	Non faulty	Non faulty
Traffic node	Non faulty	Faulty	Non faulty	Non faulty	Non faulty
End node	Non faulty	Non faulty	Non faulty	Faulty	Non faulty
Dead node	Faulty	Faulty	Faulty	Faulty	Faulty

3.4 Traffic management scheme

EEFTMR technique deals with data traffic congestion in the network. In EEFTMR, every node maintains a time interval between two different data packet transmission in the same path. A sensor node when receives a new data from other node, they first checks shortest path condition for data transmission. If the shortest path is non-faulty, and it is currently not in use, then received data is transmitted through that shortest path. However, if shortest path is in use then they transmit new data through backup path as shown in the flow diagram (Fig. 1). The received data transmission technique follows the fast come fast serve (FCFS) policy.

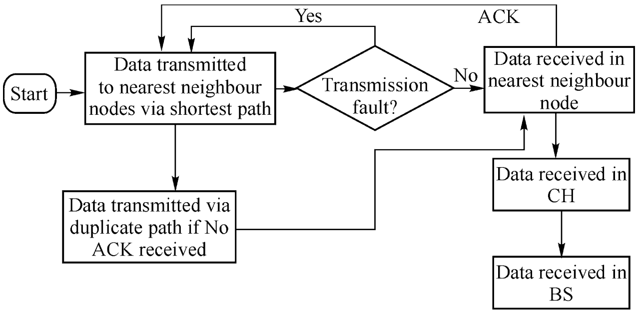


Fig. 1 EEFTMR architecture for fault tolerance

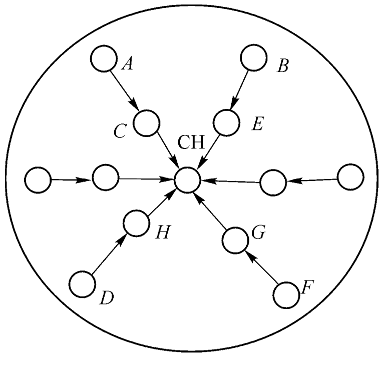
4 Proposed method for EEFTMR

In this section, we briefly describe our proposed EEFTMR technique. This section is divided into two sub section one is fault tolerant data routing another is energy efficient routing methodology.

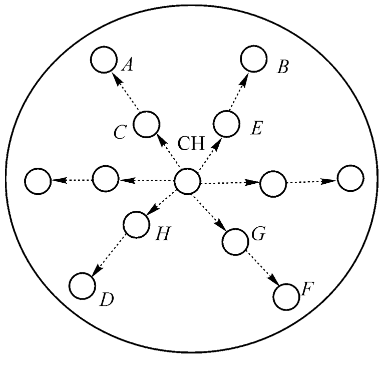
4.1 Fault tolerance data routing

In EEFTMR technique, every cluster member node transmits data to cluster head. CH collects all cluster member data. CH after aggregation data transmits to BS.

In Fig. 2(a). Cluster member nodes *A*, *B*, *D*, *F* transmits their data to CH's nearest member nodes *C*, *E*, *H*, and *G* respectively. If any node failure or transmission fault does not occurs, then after data is received by the CH's nearest member nodes *C*, *E*, *H*, and *G* send acknowledgement messages (Fig. 2(b)). In the same way, CH nearest member nodes *C*, *E*, *H* and *G* send their data to CH.



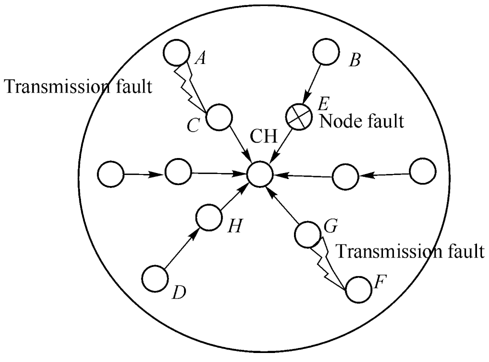
(a) Data transmission



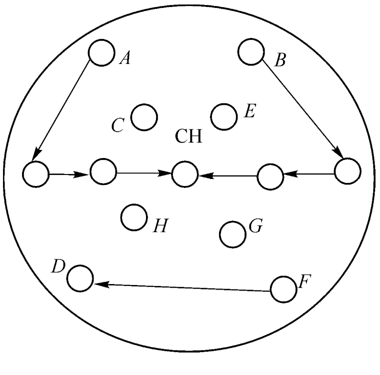
(b) ACK transmission

Fig. 2 Data transmission policy in EEFTMR technique

In the EEFTMR technique if any transmission fault or node fault occurs in the network, then source nodes *A*, *B*, *D* or *F* does not receive any acknowledge message. Therefore, they are sending their data through duplicate path. In Fig. 3(a) node *A* to *C* transmission fault occurs, hence '*A*' retransmits its sensing data to *D* node. The node *E* fails, hence '*B*' transmits its data to '*F*' node. However, node *F* does not gate any acknowledge message from *G*; hence it retransmits its data to node *D* (Fig. 3(b)). In the same way CH transmits their data to the BS in EEFTMR technique.



(a) Transmission fault



(b) Send data through duplicate path

Fig. 3 Fault recovery policy in EEFTMR technique

In EEFTMR scheme, the node collects data from nearest neighbour and transmits to the CH by a shortest path. If a node is not receiving any data from its neighbouring node for a period of time then the node sends a health message to neighbour node and waits for replay message. If all neighbour nodes replay with respect to that health message, then node decides a transitions fault occurs in previous transmission. On the other hand, if a node does not receive any replay message against health message then the node decides its receiver circuit is faulty. However, if any one of the neighbour node is not replaying against health message then the node decides that the transmitter circuit of that neighbouring node is faulty. Then it informs this to all other neighbour nodes. Sensor circuit fault is detected by the node itself by comparing its sensed data with receive data that he has been received from neighbour node. The comparison technique used here is explained in detail in Ref. [11]. If sensing information is less than the threshold value, then the node's sensor circuit is in active condition. If sensing information is grater then the threshold value, then the sensor circuit is faulty. The EEFTMR fault detection algorithm is described as below

Algorithm 1 Fault detection algorithm

```
Input: Insert all nodes into $S$ (array of nodes)
Output: Check nodes hardware condition and find out fault nodes
WHILE $S$! =Null DO
WHILE network is alive DO
    FOR each node DO
        IF node receive data from neighbour THEN
            Receiving data transmitted to shortest path
        ELSE
            Send health message all neighbour nodes
        IF receive replay all neighbour nodes THEN
            Transmission fault occurs in previous transmission
        ELSEIF not receives replay from communication node THEN
            Communication node is dead.
            Inform to all neighbour node.
        ELSEIF not receive replay from all neighbour THEN
            nodes receiver circuit fault
        END IF
        END IF
        IF Neighbour node data <= threshold value THEN
            Sensor circuit node is good
        ELSE
            Sensor circuit of comparison nodes is Faulty
            Inform to cluster head
        END IF
        IF node battery reading < threshold value THEN
            Battery fault occur
        ELSE
            Battery is good
        END IF
    END FOR
END WHILE
END WHILE
```

The EEFTMR scheme reuses the faulty sensor node depending on the node's fault condition. If the sensor circuit is faulty, then sensor node is used as a traffic node. On the other hand if the node's receiver circuit is faulty, then this node works as an end node. If a node detects its transmitter circuit, microcontroller circuit, or battery is faulty, then the node is declared as a dead node. In EEFTMR the faulty node recovery algorithm is shown below.

Algorithm 2 Faulty node recovery algorithm

```
Input: Sensor nodes hardware condition
Output: According to hardware fault condition nodes responsibility distributed
IF node detected sensor circuit fault THEN
    Declare itself as traffic node and inform all other neighbour nodes
ELSE IF receiver circuit fault occur THEN
    Declare as end node and inform all other neighbour nodes
ELSE transmitter circuit or microcontroller or batter fault occur THEN
    Declare it as dead node by the cluster head and inform other cluster member nodes
    The cluster head activate a neighbour standby node to replace the dead node.
END IF
```

4.2 Energy efficient routing methodology

In our proposed scheme, instead of initial multipath data propagation as in Refs. [13–14], it sends the data through a single shortest path. However, if data transmission faults occur in that path then it will send the data through alternative backup path. Therefore, the energy wastage for multipath data propagation can be saved in EEFTMR. Transmission energy loss of a sensor node is T_{E} [12].

$$T_{\mathrm{E}} = (\alpha_1 + \alpha_2 r^n)\beta \tag{1}$$

where α_1 is the energy loss per bit by the transmitter electronics circuit, and α_2 is the dissipated energy in the transmitter op-amp. Transmission range is r. The parameter n is power index for the channel path loss of the antenna. β is the message size which is transmitted by each node. Receiving energy loss of a node is R_{E} [12].

$$R_{\mathrm{E}} = \alpha_3 L_i \tag{2}$$

where, α_3 is energy per bit which is consumed by the receiver's electronics circuit used by the node. L_j message size which is received by each sensor node.

In non-faulty environment total energy dissipated by the EEFTMR scheme is E_{TR}. The E_{TR} is calculated by following equation

$$E_{\mathrm{TR}} = \sum_{j=1}^{N} (T_{\mathrm{E}}^i + R_{\mathrm{E}}^i) \tag{3}$$

where, N is the total number of deployed sensor nodes. On the other hand, if any fault occurs then dissipated energy by the EEFTMR is

$$E_{\mathrm{TR}}^{\mathrm{F}} = \sum_{i=1}^{N} \sum_{j'=1}^{n'} (T_{\mathrm{E}}^i + R_{\mathrm{E}}^i) j' \tag{4}$$

where, n' is the total number of paths used for any fault detection and recovery process in EEFTMR scheme.

Lemma 1 The energy loss in EEFTMR is less than multipath fault tolerant technique.

Proof A single data communication energy loss is

$E_{\mathrm{TR}} = (T_{\mathrm{E}} + R_{\mathrm{E}})$. In multipath data transmission communication energy loss is $E_{mp} = \sum_{j''=1}^{n''} E_{\mathrm{TR}}$. Where n is the number of duplicate data transmission path in multipath data routing. In EEFTMR scheme n'' value is 1 on the other hand multipath fault tolerance techniques n is always grater then 1. Therefore, energy conservation of EEFTMR is grater then to other multipath fault tolerant techniques [13–14]. The performance analysis of EEFTMR technique is discussed next.

5 Performance of EEFTMR

In this section, we present the result obtained from simulating different scenarios under different network sizes, different percentage of nodes faults and transmission faults. The simulation parameters are taken from [12]. In order to evaluate the performance of EEFTMR, four traditional metrics of WSN have been considered.

1) Global energy of network: this is the sum of residual energy of each node in the network. We calculate this value at each round of data transmission.

2) Average delay: average latency from the moment of data transmitted from source node to base station.

3) Average packet delivery ratio: number of packet transmitted to the source node and number of packet receive at the destination node.

4) Average dissipated energy: total energy loss of the network and total number of sensor nodes ratio.

Fig. 4 shows the average packet transmission delay from sensor nodes to base station in different networks size. In EEFTMR technique, data delivery time increase very slowly when node faults occurs.

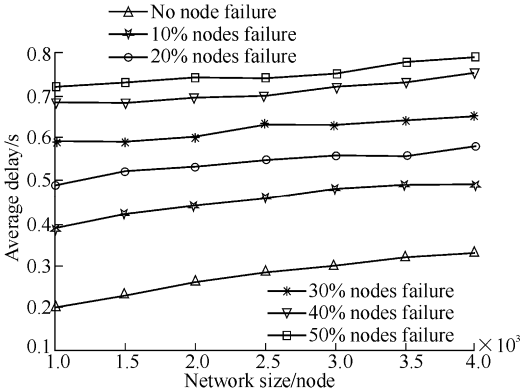


Fig. 4 Average delay in different percentage of nodes failures

The Fig. 5 shows the average packet delivery ratio (receive packet/sent packet) from sender to base station. In the EEFTMR technique, number of packet receives percentage in base station with respect to source node data transmission is very high. If any packet loss by nodes fault and path fault then backup path transmit duplicate data to cluster head as well as base station.

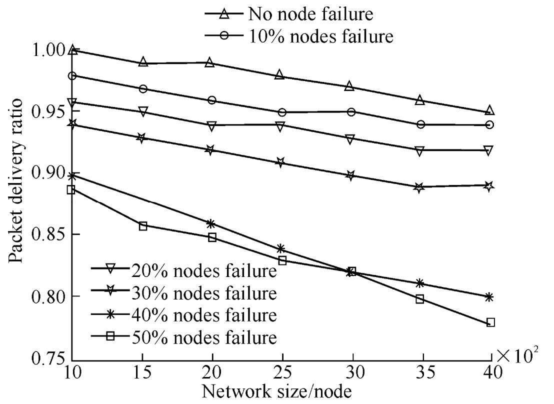


Fig. 5 Average packet delivery in different percentage of nodes failures.

In EEFTMR technique, energy loss rate of node in different network size with different percentage of nodes failures is shown in Fig. 6. When number of nodes fault percentage is low then energy loss of the networks is high because in this time maximum data is delivering to base station. If the number of node fault is increased then energy is loss of the network is decreased because in this condition data delivery to base station decreased.

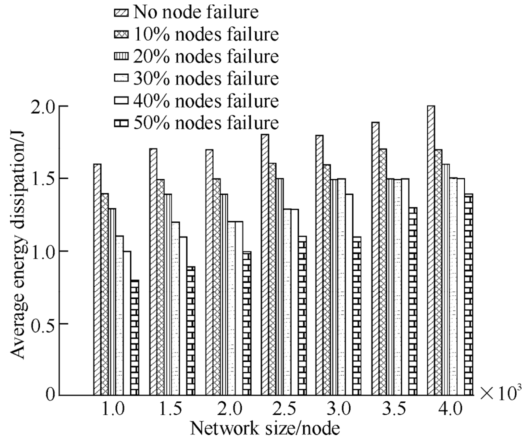


Fig. 6 Average dissipated energy in different percentage of nodes failures

Fig. 7 shows the through put of the sensor nodes with respect to main routing path failures. In EEFTMR technique throughput of sensor nodes is 49% batter in comparison to the fault-tolerant routing protocol for high failure rate wireless sensor networks (ENFT- AODV) [13] technique and 70% batter, compared to ad-hoc on-demand distance vector(AODV) [15] techniques. In the case of AODV technique, the throughput of the sensor nodes decreased rapidly when number of main path increases, because in this technique one main path have been failed then no other path is exited for retransmission of faulty data. ENFT-AODV technique used one backup path to improve retransmission of packet. If backup path fails then there is no way to transmit data to destination node. On the other hand EEFTMR technique uses two backup paths for improvement of failure recovery.

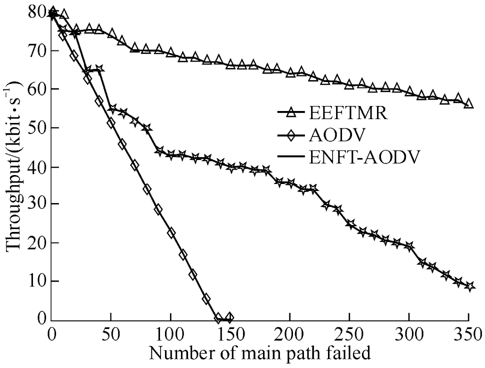


Fig. 7 Throughput with respect to main routing path fault

Fig. 8 indicates the variation of the fault diagnosis rate with the number of faulty nodes. The fault diagnosis rate manifests the number of faulty node detected in each iteration. In average case if 100 number of nodes are faulty, then approximately 95% of the faulty nodes are identified (95 out of 100), whereas approximately 70% of faulty nodes are detected (70 out of 100) in the worst case. In worst case high node failure in network leads to low fault diagnosis rate.

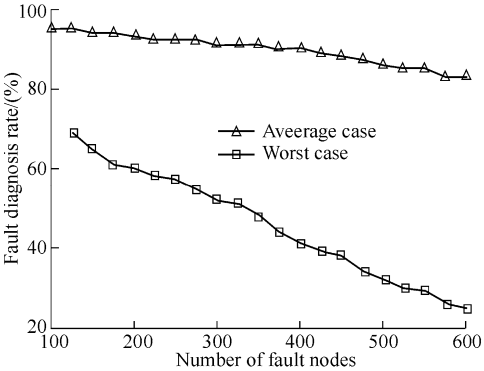


Fig. 8 Successful diagnosis rate

6 Conclusions

In this paper, we present EEFTMR as a fault tolerant multipath routing scheme for energy efficient WSN. The EEFTMR technique recovers node fault and transmission fault and transmits data in energy efficient manner. In EEFTMR technique, fault tolerant percentage is very high compared to other fault tolerant techniques. Data routing time in EEFTMR is very fast and energy aware even at high percentage of nodes fault. The EEFTMR also proposes a faulty node recovery scheme that effectively reuses or replace the faulty node. The simulation results establish that the proposed routing give better monitoring of the nodes that effectively leads to an energy efficient maximally fault tolerant in sensor network.

In future we would like to improve and analyze the time complexity of the proposed algorithm. Moreover, the performance in worst case scenario improved by efficient detection of faulty nodes.

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