

On Distributed Self Fault Diagnosis for Wireless Multimedia Sensor Networks

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ABSTRACT

This paper presents a distributed self fault diagnosis scheme for wireless multimedia sensor networks (WMSN). The sensor node makes decision about whether or not to discard its own sensor reading by using proposed sensor node architecture. Fault diagnosis is achieved by disseminating decision made at each node. The proposed scheme considers the channel impairment, where the channel is modeled as two state Markov chain. A low memory energy efficient image compression scheme [13] and Reed-Solomon coding for forward error correction is used. Analytical and simulation results show the robustness of the scheme. Both hard and soft fault situation is considered. This work also investigates the energy consumed in diagnosing a fault event.

Categories and Subject Descriptors

B.4.5 [Reliability, Testing, and Fault-Tolerance]: Diagnostics

General Terms

Reliability, Algorithms

Keywords

Fault detection, WMSN, energy efficient diagnosis.

1. INTRODUCTION

As wireless communications technology have matured in recent years, wireless multimedia sensor networks have emerged as a promising solution for a variety of remote sensing applications, including battlefield surveillance, environmental monitoring, intruder detection systems [2]. Irrespective of their purpose, all WMSNs are characterized by the requirement for energy efficiency, scalability and fault tolerance. WMSNs consisting of image sensor nodes may be deployed in unattended and possibly hostile environments increase the probability of node failure. Unlike wireless local area networks, the path between the source and the destination in wireless sensor networks normally contains multiple wireless links (hops).

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The wireless links between nodes are susceptible to wireless channel fading, which causes channel errors. Unlike conventional sensor nodes, image sensor nodes generates bulk amount of data which is routed to the sink node. Erroneous data generated by faulty sensor nodes must be protected from entering the network for effective bandwidth and energy (processing of image contributes more to energy consumption) utilization. System level diagnosis appears to be a viable solution to this problem.

The problem of fault detection and diagnosis in wireless sensor networks is extensively studied in literatures [7, 9, 12, 14]. Article [7] considers the problem of identifying faulty nodes (crashed) in wireless sensor networks. Elhadeif *et al.* [9] proposed a distributed fault identification protocol called Dynamic-DSDP for MANETs, which uses a spanning tree (ST) and a gossip style dissemination strategy. Article [14] presents a distributed fault detection algorithm for wireless sensor networks, where each sensor node identifies its own state based on local comparisons of sensed data with some thresholds and dissemination of the test results. The fault detection accuracy of a detection algorithm would decrease rapidly when the number of neighbor nodes to be diagnosed is small and the nodes failure ratio is high. Article [12] address this problem by defining new detection criteria. Most of the literatures address the fault detection and diagnosis problem in WSN by considering sensor nodes as temperature or humidity or pressure sensors. Upto our knowledge, there has been little work on the design of a fault diagnosis scheme for WMSN. Although there is considerable amount of research on fault detection and diagnosis in wireless sensor networks, the current approaches may not be suitable for WMSN. Czarlinska *et al.* [8] investigated the event acquisition properties of WISNs. These techniques include lightweight image processing, decisions from N sensors with or without cluster head fault and attack detection. Article [15] investigated the problem of image transport over error prone wireless sensor networks, where a two state Markov scheme of node transitions between an "on" and "off" state is considered. No dynamic node failure detection service is available in the network.

In this work, we propose a distributed diagnosis scheme that identifies the faulty nodes in presence of channel fault. Here, we employ a two-state Markov channel scheme, which has been proved to provide a good approximation for both, slow fading and fast fading wireless channels [17]. The proposed sensor node architecture (figure-1) constitute of four fundamental blocks: CMOS camera, source encoder and decoder, RS-encoder, wireless communication subsystem. The wireless communication subsystem of proposed architecture is conforming to the IEEE 802.15.4 [1], i.e. standard for Zigbee PHY and MAC layer. Each block is subject to failure, which results in system failure. The proposed scheme investigates the fault occurred in each block.

2. MODELING AND PROBLEM STATEMENT

2.1 Network model and assumptions

The proposed scheme considers a densely deployed wireless sensor network, which includes camera-equipped nodes. We assume that there are N sensor nodes non-uniformly distributed in a square area of side L , which is much larger than the communication range of the sensors. A cluster based routing mechanism as proposed in [16] is assumed to be in place, where periodic reclustering can select nodes with higher residual energy to act as cluster heads. A cluster head maintains a membership list of its cluster nodes. Nodes are organized into one-hop clusters. Every node is aware of its cluster head. Every cluster head knows the path(s) to its neighboring clusters as well as the path(s) to the sink.

The proposed scheme assumes static fault situation i.e no node is allowed to be faulty during diagnosis period T_{diag} . The network topology remains static during T_{diag} . Links are symmetric, i.e., two nodes v_i and v_j can communicate using the same transmission power level. Energy consumption is not uniform for all nodes. All nodes have similar capabilities (processing/communication), and equal significance. Communication channels between the nodes have bounded delay. Each node can estimate its channel error probability.

2.2 Architecture of Proposed Wireless Image Sensor Node

This section commences by describing the architecture of the proposed image sensor node. The proposed architecture constitute of four fundamental blocks: CMOS camera, source encoder, RS-encoder and wireless communication subsystem (figure1).The proposed architecture uses CMOS image sensor, as the performance of CMOS image sensors is very promising compared to CCDs. A fault-tolerant architecture [5] can tolerate up to certain pixel failure rate(PF_{rate}), beyond which the quality reduction QR of a corrected image may not be acceptable.

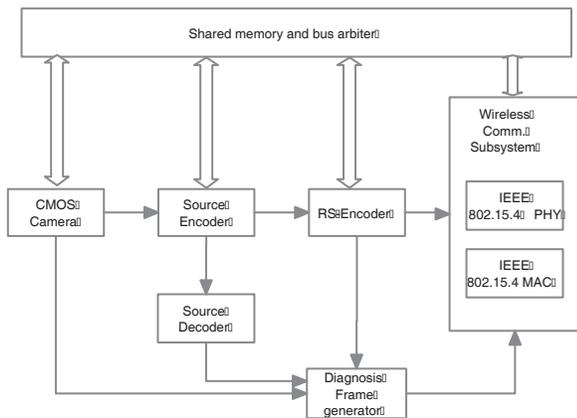


Figure 1: Architecture of Proposed Wireless Image Sensor Node

Uncompressed raw image data require excessive bandwidth for a multi-hop wireless environment. Conventional image compression algorithms are not suitable for resource-constrained wireless sensor networks because they require complex hardware and make the energy consumption for computation comparable to communication energy dissipation. The proposed architecture uses [13] to compress an image. In our proposed scheme, the source encoder takes only a 8×8 image part from frame memory of CMOS Image sen-

sor for self diagnosis. To evaluate image quality, proposed scheme compares the original 8×8 image $f(j, k)$, $j, k = 1, \dots, 8$, with the reconstructed image (decoder output: figure1) $\hat{f}(j, k)$, $j, k = 1, \dots, 8$. The Mean Squared Error (MSE) is calculated as

$$MSE = \frac{1}{64} \sum_{j,k} (f(j, k) - \hat{f}(j, k))^2 \quad (1)$$

The PSNR in decibels (dB) is calculated as

$$PSNR = 10 \cdot \log_{10} \frac{(2^b - 1)^2}{MSE} \quad (2)$$

The proposed scheme uses $b = 8$ -bits gray scale image.

The proposed architecture uses Reed-Solomon (RS) codes to identify and correct errors in transmission. A self-checking RS encoder [4] is used. The fault-free behavior of the checker, when a correct set of inputs is provided is the following: the output codes (PC_{out}) 01 or 10 are generated for an odd parity checker or the output codes 00 or 11 for an even parity checker. Here, we consider even parity checker.

The wireless communication subsystem of proposed architecture is compliant to the IEEE 802.15.4 [1], i.e. standard for Zigbee PHY and MAC layer. The IEEE 802.15.4 MAC layer contains a handful of services for different algorithms and control flows: beacon and superframe management for network synchronization, CSMA/CA as channel access method and automatic ACK. Our scheme assumes that fault in the communication subsystem will make the sensor node dissociate from the network. Each device in ZigBee contains information about those devices located within its transmission range. This information is held in a table called the neighbor table.

2.3 Fault Model

The proposed scheme considers both hard and soft fault. In hard-fault situation the sensor node is unable to communicate with the rest of the network (communication subsystem is faulty or battery is drained or node is completely damaged), whereas a node with soft-fault continues to operate and communicate with altered behavior (other blocks may be faulty). These malfunctioning (soft faulty) sensors could participate in the network activities, since; still they are capable of routing information.

The scheme we use for channel is a two-state Markov channel scheme [10] with two states : G (good) state and B (bad) state. In the good state, the bits are received incorrectly with probability P_{good} and in the bad state, the bits are received incorrectly with probability P_{bad} . For this scheme it is assumed that $P_{good} \ll P_{bad}$. to simulate burst noise, the state of B and G must tend persist: i.e., the transition probability $T_{GB} = P(G \rightarrow B)$ and $T_{BG} = P(B \rightarrow G)$ will be small and the probability of remaining in G and B is large. The steady-state probability of a channel being in the bad state is $P_B = T_{GB}/(T_{GB} + T_{BG})$. the average bit error probability of the channel is $P_e = P_{bad}P_B + P_{good}(1 - P_B)$.

2.4 Energy Consumption Model

Traditionally, digital signal processing power consumption has been ignored in system design, since transmit power has been the most significant component. However, for image processing algorithms used at higher data rates, signal processing power consumption becomes an issue. In our scheme first order radio scheme [11] is used to formulate the energy consumed by transceiver system. The energy consumed in transmitting a bit to distance d , E_{Tx} , and

the energy in receiving a bit, E_{RX} , are respectively

$$E_{TX} = E_{elec} + \epsilon_{amp} \times d^\alpha \quad (3)$$

$$E_{RX} = E_{elec} \quad (4)$$

Where E_{elec} is the energy consumed by the transmitter/receiver electronics per bit, ϵ_{amp} is the energy dissipated by power amplifier in Joules per bit per m^2 and α is the path loss parameter. The proposed scheme takes α as 2. The energy consumed by the image processing unit:

$$E_{DIP} = E_{CP} + E_{RSE} \quad (5)$$

Where E_{CP} and E_{RSE} are the energy dissipated for image compression and RS encoding per information bit, respectively.

2.5 The Diagnosis Problem

Assume that N nodes are dispersed in a field and the above assumptions hold. Our goal is to identify a correct set of faulty nodes. To achieve correct and complete diagnosis the following requirements (discussed in section 4) must be met:

1. Diagnosis is completely distributed. Each node independently makes its decisions based only on local information.
2. At the end of diagnosis round, each node is diagnosed as either a faulty or fault free.
3. Regardless of network diameter, diagnosis terminates within a fixed amount of time.
4. Diagnosis should be efficient in terms of processing complexity, time complexity and message exchange.

3. FAULT DIAGNOSIS SCHEME

The proposed diagnosis scheme has three main phases: (i) detection phase (ii) clustering and spanning tree(ST) building phase and (iii) dissemination phase.

The Detection Phase: In this phase, each sensor node makes a decision about whether or not to discard its own sensor reading in the face of the evidences; $PSNR$, QR and PC_{out} . A formal description of this phase is presented in algorithm-1.

Algorithm 1 Detection Phase

- 1: Obtain the sensor reading (image)
 - 2: Evaluate PF_{rate} , PC_{out} and $PSNR$.
 - 3: Broadcast IMA message.
 - 4: set timer T_{out}
 - 5: **if** $T_{out} = true$ **then**
 - 6: Declare unreported (transceiver or channel is faulty) nodes as possibly hard faulty and update fault table FT_{S_i} .
 - 7: **end if**
 - 8: **if** $PSNR < P_{th}$ or $QR \geq I_{th}$ or $RS_{status} = Faulty$ **then**
 - 9: S_i discard its own sensor reading, set status flag $F_{state} = true$.
 - 10: **end if**
-

In spite of the fault tolerant architecture [5], an image may not be acceptable if the pixel failure rate is high. Let, the probability of a half-pixel is fault-free at time t is p_c and the probability of half-pixel failing by time t is $q_c = 1 - p_c$. The quality reduction(QR) in the corrected image can be written as

$$QR = ((1 - q_c^2)^8 q_c^2 E_{SC} + 2p_c q_c E_{HC}) I^2 \quad (6)$$

Where E_{SC} and E_{HC} are the average number of errors per image caused by software and hardware correction methods respectively. The proposed scheme discards the image reading upon reaching certain threshold for QR i.e. $QR \geq I_{th}$.

The RS-encoder fault status of the proposed architecture can be mapped as follow

$$RS_{status} = \begin{cases} Faultfree & \text{if } PC_{out} = 00 \text{ or } 11 \\ Faulty & \text{otherwise} \end{cases} \quad (7)$$

The detection phase uses timeout mechanism to detect hard faulty nodes. In the proposed scheme every node maintains a neighbor table. If S_i does not receive I am alive (IMA) message from $S_j \in N(S_i)$ (where, $N(S_i)$ is the neighbor set of S_i) before T_{out} , S_i declares node S_j as possibly hard faulty (initial detection status). In our scheme S_j cannot report to S_i , if either the communication subsystem of S_j is faulty or the communication channel E_{ij} is faulty. For faulty communication channel S_i will mark S_j as hard faulty, which may not be true. Final decision regarding S_j (hard faulty or not) is taken by the cluster head as discussed in following sections. T_{out} should be cleverly chosen, such that all the fault free nodes $S_j \in N(i)$ connected by fault free channels E_{ij} must report node S_i before T_{out} .

Clustering and Building Phase: Clustering sensor nodes is an effective topology control approach and ST is the minimal graph structure supporting the network connectivity. The proposed scheme constructs a ST of the cluster heads to disseminate diagnostic information (algorithm-2). Combining this two approaches (clustering and ST) brings a noticeable increase in network lifetime. This phase follows HEED protocol [16] to select a set of cluster heads from the set of nodes in the network, and then cluster the remaining nodes with these heads. Nodes are organized into one-hop clusters. Once clustering process completed, the cluster head aggregates the fault status and the fault tables of its member nodes. To handle hard fault situation in presence of communication channel failure, the cluster head compares fault tables of the member nodes and take decision on hard fault. Let's say, FT_{S_i} has marked S_j as hard faulty but FT_{S_k} detected it as fault free, then cluster head declares S_j as fault free. If non other than S_i have any information regarding S_j , then cluster head follows FT_{S_i} . This ambiguous situation is further handled in dissemination phase. The fault table of the cluster head is now updated with these aggregated fault information. This phase then construct a ST, spanning all the cluster heads starting at sink node as root. Here, T_{STout} (inter-cluster communication time) is greater than T_{out} (intra-cluster communication time) to ensure aggregation of fault information F_{state} , fault table of cluster members and the parent-child information for cluster head in ST. The leaf cluster heads in the ST start dissemination phase.

Dissemination Phase: Once the ST has been constructed, the disseminating phase starts. All leaves of the ST, i.e. cluster heads without children, send their local diagnosis views to their parents. Each parent has to wait until it collects all its children's diagnostics. Once collected, the parent combines all of them with its own local diagnostic and updates its fault table. It then transmits the aggregated diagnostic message to its parent in the ST, and so on. The sink node collects all the local diagnostics, and it disseminates the global diagnosis view down the tree to all cluster heads. Upon receiving the global view, each cluster head communicate this global view to their member nodes. At this stage, the distributed diagnosis session terminates.

In local dissemination phase final decision on hard fault is taken. In every label of the ST, the cluster heads compare the fault tables of its children and take a decision about hard fault. The ambiguity as discussed earlier is resolved at each label of the ST and at the end of local discrimination phase the fault table of sink node has a correct set of hard faulty nodes.

Algorithm 2 clustering and ST building Phase

```
1: Start clustering process using HEED Protocol [16], avoiding
   sensors with  $F_{state} = true$  as cluster head.
2:  $parent\_flag \leftarrow false$ 
3:  $N_u \leftarrow |nodes\ in\ CH_u|$ 
   // Cluster head  $CH_u$  receives ST formation message from
    $CH_v \in N(CH_u)$ 
4: Set timer  $T_{STout}$ 
5: Obtain fault table  $FT_{S_i}$  and status flag  $F_{state}$  of sensor  $S_i$ , where
    $S_i \in CH_u$  and  $i = 1, 2, \dots, N_u$ 
6: Compare fault table  $FT_{S_i}$ ,  $i = 1, 2, \dots, N_u$  for correct set of
   hard faulty nodes
7: repeat
8:   if  $CH_u = CH_v.parent$  then
9:      $CH_u.children \leftarrow CH_v$ 
     //  $CH_v$  is now element of children set of  $CH_u$ 
10:   else if  $ParentFlag = false$  then
11:      $CH_u.parent \leftarrow CH_v$ 
12:      $parent\_flag \leftarrow true$ 
13:     Broadcast  $CH_v$  as parent of  $CH_u$ 
14:   end if
15: until ( $T_{STout} \neq true$ )
16: if  $T_{STout} = true \ \& \ CH_u.children = \phi$  then
17:   Start disseminating the diagnosis information
18: end if
```

Algorithm 3 Dissemination Phase

```
1:  $temp\_children \leftarrow \phi$ 
2:  $local\_diagnosed \leftarrow global\_diagnosed \leftarrow false$ 
3: repeat
4:   if  $CH_v \in CH_u.children$  then
5:     Compare  $FT_{CH_u}$  with  $FT_{CH_v}$  for correct set of hard
     faulty nodes.
6:     Update fault table  $FT_{CH_u}$  with  $FT_{CH_v}$ .
7:      $temp\_children \leftarrow temp\_children \cup CH_v$ .
8:     if  $|CH_u.children| = |temp\_children|$  then
9:       Broadcast  $FT_{CH_u}$ 
10:    end if
11:   else if  $CH_u = sink$  then
12:     Start global dissemination by broadcasting  $FT_{sink}$ .
13:      $local\_diagnosed \leftarrow true$ 
14:   end if
15: until ( $local\_diagnosed = false$ )
16: repeat
17:   if  $CH_u.parent = CH_v$  then
18:     Update fault table  $FT_{CH_u}$  with  $FT_{CH_v}$ 
19:     Broadcast  $FT_{CH_u}$ 
20:     if  $CH_u.children = \phi$  then
21:        $global\_diagnosed \leftarrow true$ 
22:     end if
23:   end if
24: until ( $global\_diagnosed = false$ )
```

4. CORRECTNESS AND COMPLEXITY

In this section, we analyze three performance metrics of the proposed scheme in a multi-hop wireless network; energy consumption, time and message complexity. The proposed scheme described in algorithms- 1,2 and 3 meets the requirements listed in Section-2.5, as discussed next.

OBSERVATION 1. *The proposed scheme is completely distributed (requirement 1). Each sensor node makes a decisions about whether or not to discard its own sensor reading in the face of the evidences PSNR, QR and PC_{out} . Initial decision regarding hard faulty nodes are taken at each node and the final decision is made in subsequent stages of dissemination.*

OBSERVATION 2. *It is evident from observation-1 that at the end of the dissemination phase each node is diagnosed as faulty or fault free(requirement 2).*

The upper bound time complexity will be expressed in terms of the following bounds:

T_p : an upper bound to the time needed to propagate a message between cluster heads.

T_{dip} : an upper bound to the time required to encode(compression and RS-encoding) the image.

LEMMA 1. *The proposed diagnosis algorithm terminates before time $T_{dip} + 3d_{st}T_p + T_{STout} + T_{out}$. Where, d_{st} is the depth of the spanning tree. (requirement 3).*

PROOF. The detection phase takes at-most $T_{dip} + T_{out}$ time in detecting its own status and obtain initial detection status of hard faulty nodes. In ST building phase, the farthest cluster head generates its ST building message in at most $d_{st}T_p$. The cluster head to generate this type of messages should wait for T_{STout} before discovering that they are the leaves of the ST. In this phase cluster heads ask their member nodes to send their diagnostics that requires T_{out} time where, $T_{out} < T_{STout}$. Thus, ST building phase needs $d_{st}T_p + T_{STout}$ time to complete. In at most $d_{st}T_p$, the sink node has collected all diagnostic views and disseminates the global diagnostic view that reaches the farthest mobile in at most $d_{st}T_p$. Thus, the disseminating phase requires $2d_{st}T_p$ time to complete. Now, the upper bound time complexity can be expressed as

$$T_{cost} = T_{dip} + 3d_{st}T_p + T_{STout} + T_{out} \quad \square$$

LEMMA 2. *The proposed scheme has a worst-case message exchange complexity $O(N)$ in the network (requirement 4).*

PROOF. The diagnosis starts at each node by sending the IMA message to neighbors costing one message per node i.e. N messages in the network. In next phase each node communicates their diagnostics to their cluster head costing $N - n_c$ messages exchange. Building ST of cluster heads with sink as root costs $n_c + 1$ message exchange. Each cluster head, excluding the sink, sends one local diagnostic message. Each cluster head, excluding the leaf cluster heads, sends one global diagnostic message and in worst case depth of ST is n_c . Thus, Message cost for disseminating diagnostic messages is $2n_c$. Now, the total number of exchanged messages is $M_{cost} = 2(N + n_c) + 1 = O(N)$ \square

4.1 Energy Consumption

Based on the description of the proposed scheme, each node encodes the captured image and broadcast IMA message. The energy cost image compression, RS encoding and sending IMA message to neighboring nodes is given by

$$E_1 = m(rE_{CP} + rE_{RSE}) + n_{IMA}E_{TX} \quad (8)$$

Where m and n_{IMA} are the number of bits per symbol and per IMA message respectively. The energy consumed in image compression per bit is E_{CP} :

$$E_{CP} = E_{pre} + E_{code}$$

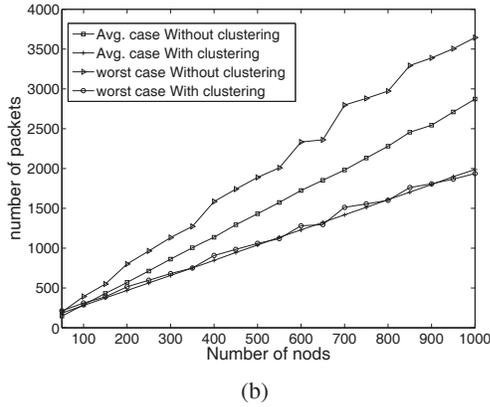
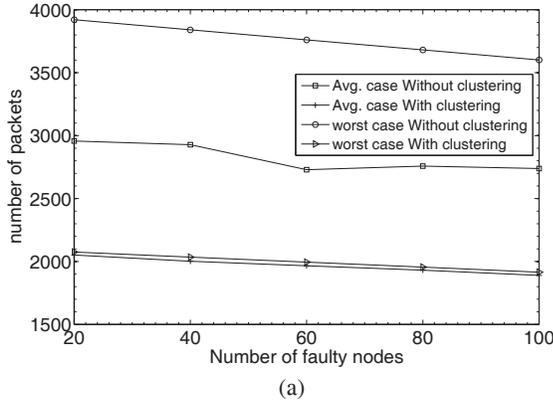


Figure 2: Message complexity

Where E_{pre} is the energy dissipated in optimized DCT and quantization. E_{code} is the energy spent in coding. The energy spent in receiving IMA message form M neighbors is

$$E_2 = Mn_{IMA}E_{RX} \quad (9)$$

Now, the energy cost in detecting the status of a node is

$$E_{detect} = f(E_1 + E_2) \quad (10)$$

At this stage each cluster head ask its member nodes to send their fault table and the energy spent in this process is

$$E_3 = \sum_{i=1}^{n_c} (n_r + n_{ft}M_{c_i})E_{TX} + (n_r + n_{ft})M_{c_i}E_{RX} \quad (11)$$

Where n_c is the number of cluster heads, M_{c_i} is the number of member nodes of i^{th} cluster head, n_r is the number of bits per cluster head request for fault table, n_{ft} is the number of bits per fault table. The energy spent in building ST of cluster heads is given by

$$E_4 = n_{st} \left(\sum_{i=1}^{n_c} (E_{TX} + E_{RX}) + \sum_{\forall i \neq \text{leaf node}} n_{children_i} E_{RX} \right) \quad (12)$$

Where $n_{children_i}$ is the number of children of cluster head i and n_{st} is the number of bits per ST building message. The energy cost in disseminating diagnostic information is given by

$$E_{local} = n_{ft} \left(\sum_{i=1}^{n_c} E_{TX} + \sum_{\forall i \neq \text{leaf node}} E_{RX} \right)$$

$$E_{global} = n_{ft} \left(NE_{RX} + \sum_{\forall i \neq \text{leaf node}}^{n_c} E_{TX} \right)$$

$$E_5 = E_{local} + E_{global} \quad (13)$$

Now, the energy spent in disseminating diagnostic information is

$$E_{diag} = f(E_3 + E_4 + E_5) \quad (14)$$

Finally, the total energy consumption of the proposed scheme is

$$E_{overhead} = \frac{E_{detect} + E_{diag}}{N} \quad (15)$$

5. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed scheme via simulations. The set of simulation parameters are summarized in Table1. We use an RS code with $m = 8$ bits per sym-

Table 1: Simulation Prameters

Parameter	Value
Number of sensors	100-1000
Topology size	1000m × 1000m
Cluster head radius	50m
Propagation delay	10μsec.
Propagation scheme	Two Ray Ground
Antenna scheme	Omni directional

bol, $n = 255$ and $R = 223$ with the assumption that the channel error probability estimate at each node is 10^{-3} . For simplicity, in the simulation, we choose $P_{good} = 0$ and $P_{bad} = 1$. We fix $T_{BG} = 1/8$ and vary T_{GB} to get different channel error probabilities P_e . The typical values for wireless communication energy scheme are: $E_{elect} = 5 \times 10^{-9}$ Joule/bit and $\epsilon_{amp} = 100 \times 10^{-12}$ Joule/bit/m². For RS-encoder the value for energy is calculated using [3] as 0.08×10^{-9} Joule/bit and time cost of 1.02 msec to encode bit stream for 8×8 image. The energy cost of image compression is $E_{CP} = 89.81 \times 10^{-6}$ Joule and equal amount of energy cost for decoding. The time consumed in compression is 4.08msec [13](for 8×8 image). The threshold vales for $P_{th} = 25dB$ and $I_{th} = 30\%$ pixel failure rate. Every result shown is the average of 100 experiments. Each experiment uses a different randomly-generated topology.

Table 2: Comparison with related works

	Message complexity	Time complexity
[6]	$Nd_{max} + N(N + 1)$	$\delta_G T_{gen} + \delta_G T_p + T_{out}$
[9]	$Nk + 3N - 1$	$\delta_G T_{gen} + 3d_{st} T_p + 2T_{out}$
[7]	$3N - 2$	$\delta_G T_{send} + d_{st} T_p + T_{out}$
Proposed	$2(N + n_c) + 1$	$T_{dip} + 3d_{st} T_p + T_{STout} + T_{out}$

d_{max} : The maximum of the node degree

δ_G : The diameter of graph G.

T_{send} : The upper bound to the time need to solve contention.

T_{gen} : upper bound to time between reception of the first diagnostic message and the generation of test request. d_{st} : Depth of the ST.

k : connectivity of the network.

Figure 2 clearly shows the communication complexity of the proposed scheme. Figure 3 presents the total diagnosis time of the proposed algorithm. From the simulation results it is evident

that, the proposed clustering and spanning tree based approach has a significant improve in performance from both time and message complexity prospective. Figure 4 presents the total energy consumed by the network in diagnosing the network. As desired the energy cost decreases with decrease in network size.

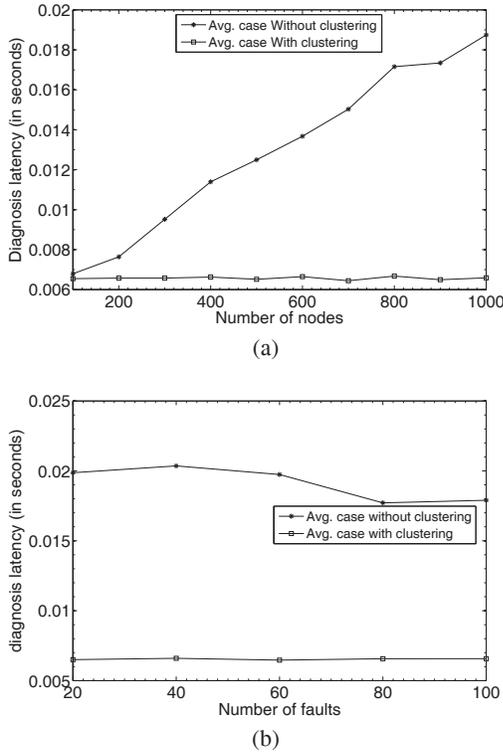


Figure 3: Time complexity

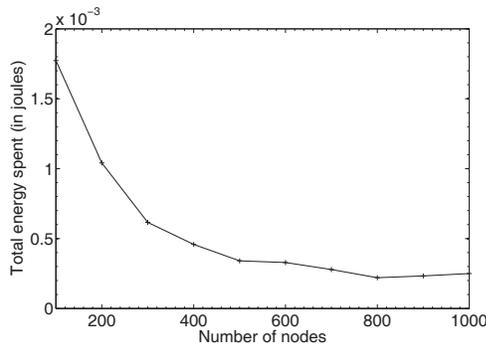


Figure 4: Energy complexity

6. DISCUSSION

This paper addresses the fundamental problem of identifying faulty (soft and hard) nodes in a WMSN. Both the time and message complexity is compared with schemes proposed in [6, 7, 9]. The proposed scheme outperforms that of these self diagnosis schemes from both time and message complexity prospective. Both the message and time complexity of our scheme is $O(N)$ for an N -node WMSN.

An interesting open question is whether a self diagnosis algorithm for dynamic fault situation in a time varying WMSN with lower message cost can be developed that can either have same or less latency. In the future work we are investigating this open question.

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