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CHFM: Cluster-based and Hierarchical Fault Management to Fault Detection and Network Connectivity Recovery in Wireless Sensor Networks

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Abstract: Due to the shared wireless communication medium, harsh developed environments and resources limitation, wireless sensor networks (WSN) are inherently fault-prone. Among these limitations, energy problem is one of the most constraining factors and node failure due to crash and energy exhaustion is usual. It is essential for the WSN to be able to detect faults early and institute recovery actions in order to avoid destruction of service due to faults. In this paper we propose a cluster based method for fault detection and network connectivity recovery which uses some of the nodes as gateway nodes in the network for implementing of voting mechanism. Simulation Results show that the proposed algorithm is energy efficient and its performance is more efficient than previous ones.

Key words: Index Terms-wireless sensor network; fault management; cluster-based; energy efficiency.

INTRODUCTION

In the recent years, the advances in micro-electro-mechanical systems (MEMS), small scale energy supplies, low power electronics, tiny microprocessors, and low power radio technologies have created low power, low cost wireless sensor devices, which can sense and react to changes in their environments. These sensors are equipped with a battery, a radio transceiver, a tiny microprocessor, and a set of transducers that used to gathering the information that report the changes in the environment of the sensor node. The emersion of these low cost and small size wireless sensor devices has motivated research in the last years addressing the possibility of collaboration among sensors in data collection and processing, which led to the creation of Wireless Sensor Networks.

A typical WSN consists of a number of sensor devices that collaborate with each other to perform a common task (e.g. target tracking, environment monitoring, etc) and report the aggregated data through wireless interface to a sink node. The areas of applications of WSNs vary from healthcare, civil and environmental to military. Examples of applications include target tracking (Bokareva, 2006), habitat monitoring (Mainwaring, 2002) civil structure monitoring (Xu, 2004) forest fire detection (Hefeeda, 2007) and factory maintenance (Srinivasan, 2005).

Due to the deployment of a large number of sensor nodes in uncontrolled or even harsh environments, it is common for the sensor nodes to become faulty and unreliable. Fault is an incorrect state of hardware or a program as a result of a failure of a component (Koushanfar, 2002). Some of the faults result from systems or communication hardware failure and the fault state is continuous in time. For example, a node may die due to battery depletion. In this paper we consider only permanent faults, which when disregarded would cause loss in connectivity problem.

Faults occurring due to energy depletion are continuous and as the time elapse these faults may increase, resulting in a non-uniform network topology. This often results in cases where a certain part of the network becomes energy constrained before the other parts of network. The problems that can occur due to sensor failure are loss in connectivity and delay due to the loss in connection. Therefore, to overcome sensor node failure and to guarantee the system reliability, faulty nodes should be detected in the minimum possible time and appropriate acts to recover connectivity must be taken to accommodate for the faulty node.

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Also, the power supply on each sensor node is limited, and frequent replacement of the batteries is not practical due to the large number of the sensors in the network. Clustering algorithms such as LEACH (Heinzelman, 2000) and HEED (2004) saves energy and reduces network contention by enabling locality of communication.

The localized fault detection method has been found to be energy-efficient in comparison with another algorithm proposed in (Chessa, 2002). Crash faults identification (CFI) (Chessa, 2002) performs fault detection for the sensor network. It does not propose any method for fault recovery. This paper proposes a cluster based fault management scheme namely CHFM which detects the problems that are caused by energy depletion in nodes and then rectifies the connectivity of networks. CHFM selects the some nodes as gateway nodes to implements the voting mechanism for detecting the faulty nodes. When a sensor node fails, the connectivity is still maintained through used policies by CHFM for connectivity recovery.

The rest of the paper organized as follows: we explain the related works in section 2. Section 3 describes the proposed algorithm with details. Section 4 explore the simulation parameters and result analysis. Final section is containing of conclusion.

II. Related Works

In this section, we briefly review the related work in the area of fault detection and connectivity recovery in wireless sensor networks. Many algorithms have been proposed for fault detection and fault repair in sensor networks (Chessa, 2002; Ding, 2005; Krishnamachari, 2004; Gupta, 2003). Cluster based technique for fault detection and repair has also been proposed by Gupta in (2003). Hybrid sensor networks make use of mobile nodes to detect and recover from faults (Mei, 2006; Wang, 2005; Le, 2006).

A failure detection technique using management architecture for WSNs called MANNA, is proposed and evaluated in (Ruiz, 2004). It has the global outlook of the network and can accomplish complex tasks that would not be possible inside the network. However, this approach requires an external manager to accomplish the centralized diagnosis and the communication between nodes while the manager is expensive for WSNs. Several localized threshold based decision techniques were proposed by Iyengar (Krishnamachari, 2004) to detect both faulty nodes and event regions. In (Ding, 2005) a faulty sensor identification algorithm is proposed and analyzed.

In (Lai, 2007) a distributed fault-tolerant scheme namely CMATO is proposed for sensor networks. It assumes the cluster as an individual whole and uses the monitoring of each other within the cluster to fault detection and recover in an energy-efficient scheme. In fault recovery mechanism of this algorithm the sensor nodes within the cluster which its cluster head is faulty join to the neighbor cluster heads which is closest to them.

There have been several research works on fault management in sensor networks. The authors in (Wang, 2003) proposed the sensor deployment algorithm which moves sensors to provide an initial coverage. The authors in (Ganeriwal, 2004) suggested an algorithm called Coverage Fidelity maintenance algorithm (Co-Fi), which uses mobility of sensors to repair the coverage loss. To repair a faulty sensor, the work in (Wang, 2005) proposes a protocol to locate the closest redundant sensor node, and use the cascaded movement mechanism to relocate the redundant sensor node. In (Le, 2006) the authors proposed a policy-based structure for fault repair in wireless sensor network, and proposed a centralized protocol for faulty sensor replacement. These mechanisms outline the methods by which mobile sensor move to replace the faulty node. However, movement of the sensor nodes and also moving to an exact place to replace the faulty node to repair connectivity are energy consuming.

III. Proposed Protocol:

Due to the large impact of the permanent faults in the cluster head side, in this paper we explore the fault-tolerant mechanism for the permanent faults in the cluster head side.
In this section, we explain the components which considered in proposed algorithm with details.

A. Network Model:

Let us consider a sensor network which consists of *N* nodes uniformly deployed over a square area with high densely. There is a sink node located in the field, and the nodes use multi-hop routing to send data to it. We assume cluster heads have overlapping area and also assume all nodes, including the cluster heads and the normal nodes, are homogeneous and have the same capabilities, and they use power control to vary the amount of transmission power which depends on the distance to the receiver.

This paper deals with the fault detection and network connectivity recovery mechanisms after the stage of cluster formation. In this paper we assume that the clusters are somewhat overlap.

As can be seen in Fig. 1, this algorithm selects a node as a gateway node in each cluster using (1). The selected node firstly has maximum remained energy and secondly has maximum number of cluster heads in its neighborhood.

$$Merit\_Value_{Gateway} = \alpha(\frac{E_r}{E_m}) + (1-\alpha)(\frac{N_{NCH}}{N_{ACH}}) \quad (1)$$

Here, E_r is the remaining energy of the node and E_m is the amount of its initial energy. N_{NCH} of a node is the number of cluster heads which is in its transmission radio range and N_{ACH} is the number of all cluster heads in network. Parameter a determines the weight of each ratio.

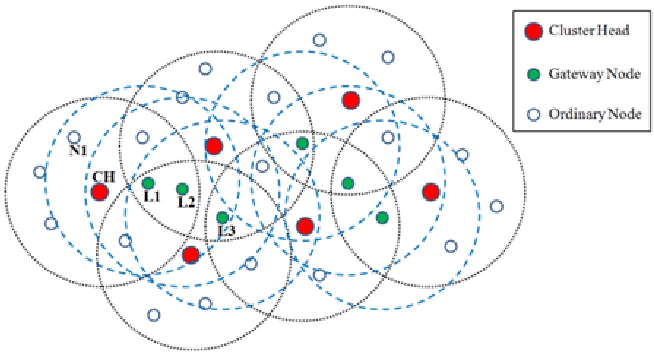

Fig. 1: Network model in CHFM.

B. Energy Consumption Model:

In CHFM, energy model is obtained from (Heinzelman, 2000) that use both of the open space (energy dissipation d^2) and multi path (energy dissipation d^4) channels by taking amount the distance between the transmitter and receiver. So energy consumption for transmitting a packet of l bits in distance d is given by (2).

$$E_{Tx}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2 & , \mathrm{d} \le \mathrm{d}_0 \\ lE_{elec} + l\varepsilon_{mp}d^4 & , \mathrm{d} > \mathrm{d}_0 \end{cases} \quad (2)$$

Here d_0 is the distance threshold value which is obtained by (3), E_{elec} is required energy for activating the electronic circuits. ε_{fs} and ε_{mp} are required energy for amplification of transmitted signals to transmit a one bit in open space and multi path models, respectively.

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}. \quad (3)$$

Energy consumption to receive a packet of l bits is calculated according to (4).

$$E_{Rx}(l) = lE_{elec} \quad (4)$$

C. Fault Detection:

In this section, we discuss method to detect the permanent faults in the cluster heads and report the same to the respective members of the clusters. This detection is essential for the cluster members as they have to invoke mechanism for the repair and recovery of those faults so as to keep the cluster connected.

There are many cases in which the cluster members could aware the aliveness of their cluster heads. For example, when the cluster members send the sensed data to the cluster heads, the cluster heads may reply through short acknowledged packets. When a node recognizes that cluster head of its cluster is fault, send a beacon message (fail report message) to gateway node of its cluster immediately before doing any other operation to challenge the other nodes of its cluster. Then this gateway node uses voting mechanism with other gateways which are in its transmission radio range to detect the status of its cluster head. Using this algorithm, if diagnosis of a node is wrong (the wrong diagnosis can arise because of medium faults), other nodes do not spend their energy for this diagnosis.

For example in Fig. 1, assume that medium between *N1* and *CH* is broken temporarily. In this case *N1* diagnosis that the *CH* is fault. So *N1* sends a beacon message to the gateway node *L1* which is in its cluster to announce it on this fault. Then *L1* calls *L2* and *L3* which are in its neighbor to cooperation. In other words, L1 uses the voting mechanism with assistance of *L2* and *L3*. *L1* will take the final decision about aliveness or failure of *CH* in any case. If determined that *CH* is faulty, *L1* broadcasts a beacon message (*CH* failure announcement message) to all nodes in its cluster. Neighboring cluster heads are informed of this failure by *L2* and *L3*.

D. Fault Recovery:

In this section, we discuss the mechanism for fault recovery. The fault recovery here refers to the connectivity recovery after the cluster head has failed. The cluster head faults discussed here are confined to failure due to energy exhaustion. The fault recovery mechanism is performed locally by each cluster.

If cluster head is declared failed, all the cluster members would be notified through the broadcasted CH-fail messages from gateway node. This message also includes a cluster head advertisement. In other words, gateway node declares itself as a cluster head. Then each cluster members selects the best one among gateway node and all cluster heads which are in its transmission radio range as a cluster head by

$$Competence\_Value = \frac{E_n + E_{ch}}{(D_{n\_ch} + D_{ch\_s})^2} \tag{5}$$

Here, E_n is the remaining energy of cluster member and E_{ch} is remaining energy of neighbor cluster head or gateway. D_{n_ch} is the distance between cluster member and neighbor cluster head and D_{ch_s} is the distance between cluster head and sink. Each cluster members selects the one that has a greatest competence value.

IV. Simulation and Performance Evaluation:

In this section, we present and discuss the simulation results for the performance study of CHFM protocol. We used GCC to implement and simulate CHFM and compare it with the CMATO and Gupta protocol.

The network is clustered using the LEACH and HEED clustering algorithms, the cluster heads then organize into a spanning tree for routing. We implement CHFM in both LEACH and HEED protocol. The transmission ranges were varied from 40 m to 100 m. Simulation parameters are presented in Table I and obtained results are shown below. Fig. 2 shows the average energy loss for fault detection in CHFM, CMATO and Gupta. In this evaluation, we change the transmission range at the all nodes, and measure the energy loss for fault detection. As it can be seen, proposed protocol has performance better than others in average energy loss for fault detection.

Table I: Simulation Parameters.

Parameters	Value
Network area	200 meters × 200 meters
Sink location	(0, 0)m
Number of sensors	100
Initial energy	2J
Eelec	50 nJ/bit
ε_{fs}	10 pJ/bit/m2
ε_{mp}	0.0013 pJ/bit/m4
d0	87 m
EDA	5 nJ/bit/signal
Beacon packet size	20 bytes
Data packet size	4000 bytes

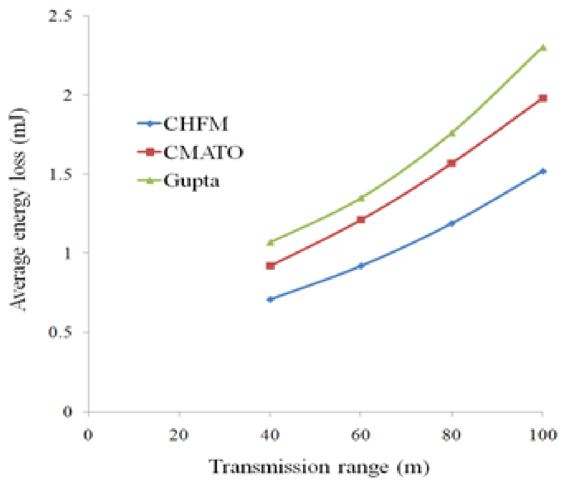

Fig. 2: Average energy loss for fault detection.

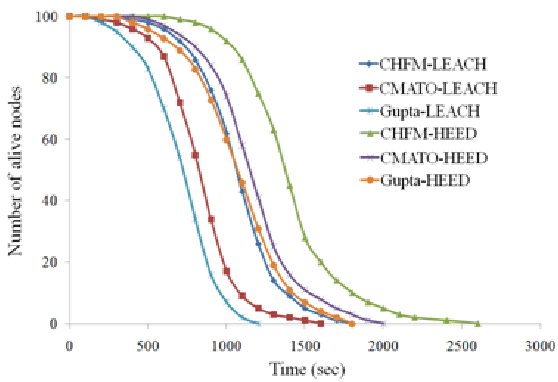

Fig. 3: Network lifetime.

Conclusion:

In this paper we propose a localized cluster based method namely CHFM for fault detection and network connectivity recovery which is energy efficient. Simulation Results show that the CHFM consumes less energy for fault detection and uses the new energy efficient method to fault recovery that prolongs the network lifetime.

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