FINITE STATE AUTOMATA BASED FAULT TOLERANT AND ENERGY EFFICIENT ROUTING (FSA-FTEER) IN WIRELESS SENSOR NETWORKS

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Abstract— *With the availability of low power, tiny and inexpensive devices, wireless sensor networks have been used for a wide variety of applications ranging from industrial to environmental monitoring and military uses. Wireless Sensor nodes are mainly used in mission critical applications and deployed in sensitive areas due to which they can't be replaced frequently. Certain situations may arise where the nodes in network may not function properly due to failures, and they become unavailable to the network. There is much need to develop energy efficient and fault tolerant routing for wireless sensor networks. We propose a (FSA-FTEER) protocol which creates multiple node-disjoint paths from source to destination and ensures that paths don't interfere with each other. Residual energy of sensor nodes is taken in to consideration as heterogeneous nodes are deployed in network.*

Keywords- Finite State Automata, Probability, Congestion, Interference, Faulty Nodes

1. Introduction

Wireless Sensor network's (WSN) are mostly deployed in hazardous areas to detect any change in environment and send information to nearest base station for certain action to be taken. These WSN's are used in wide variety of applications such as home automation, vehicle tracking, target detection, control of actuators, etc. Their (WSN's) most significant work has been in environmental monitoring (air, soil, temperatures, etc) and military applications where topology of the network, energy-efficiency, and fault tolerance of the network play a great role. With a rapid growth in technology and cost reducing measures used sensor nodes are mostly available for low cost. There is also great increase in demand of WSN's due to low-processing power, energy efficiency, tiny devices and the type of environments in which they operate. The communication between them is mostly distributed in nature as opposed to centralized framework .In this sense they consume very less energy in terms of processing the data and memory of node will be utilized efficiently.

The main role of these nodes is to detect any changes in deployed area and use a routing protocol to transmit data to base station. The paths from node to base station (sink) are node-disjoint and multi-path in nature. Node-disjoint path will help us to send data even though there are some faulty nodes in network. Multi-path mechanism is used to reduce congestion in network and it provides load balancing. The multi-path is calculated taking intermediate link information between the adjacent nodes. These node-disjoint multi-paths should be non-interfering since interference of the paths will make node to be in active state and listen to unnecessary data which results in excess energy consumption. Congestion in the network will reduce life time of the network since lost packets need to be sent again. The bandwidth of network will be over-utilized and latency of packets will be increased. Certain congestion control mechanisms must be used such as adjusting of data rates or splitting of packets in to the available multi-paths in the network.

Based on application requirements and environmental conditions topology of network is important since nodes are highly mobile. With this mobility nodes will change their positions with respect to network and, there is a high need to guarantee certain delivery rate. Network consists of different heterogeneous nodes and these nodes vary in energy consumptions. Hence residual energy of intermediate nodes should be taken in to consideration while measuring efficiency of the path. Many fault tolerant [1-10] routing algorithms are proposed in WSN. Most of them are based on TDMA where fixed slots are allocated for data transmission and the number of faulty stations was assumed to be very small. They are mostly based on cross layer optimization approach with delay and other routing metrics. Network was assumed to be static in most cases. Energy efficient routing protocols [11-27] were based on geographic, tree, coverage ratio, flooding, cross layer strategy, fusion and slot based approach. Most of these existing protocols did not consider mobility and heterogeneous factors in them.

2. Related work

Fault-tolerant routing protocols ensure that network remains connected and communication takes place in presence of certain faulty stations. A K- degree Anycast Topology Control (k-ATC) [1] protocol was proposed where network functions effectively when there are k-1 sensor nodes. This protocol mainly consists of 3 sub-algorithms i.e. (i) greedy routing algorithm will minimize the transmission range (ii) distributed algorithm ensures that connectivity of nodes is met and (iii) k-approximation algorithm. However the constraint was protocol is unidirectional. Apart from this many other routing protocols [2], [3], [4], [5] were proposed in WSN which are fault tolerant and network is k-vertex connected. Communication happens in presence of faulty nodes which is based on mixed integer programming and it's both unidirectional and bidirectional.

A Fault tolerant protocol on permutation routing [6] was proposed where p stations in network are sender and receiver of (n/p) packets. Permutation routing problem is single hop routing and, each station is in transmission range of all other stations which are present in network. The protocol is suitable for unbalanced routing permutation where each of individual nodes has unequal no of packets. However in this protocol it was assumed that no of faulty stations were small in number.

Flow control is necessary in WSN to maintain end-end delay of packet and to avoid congestion in the nodes so that packet drop rate can be reduced. A Dynamically configurable message flow control [7] for adaptive routing was proposed which is based on pipelined networks. Flow control mechanisms are used at lower layers and 2-phase routing protocols are used to avoid faulty nodes and deadlock configurations. DFT-MSN [8] is fault-tolerant routing algorithm in WSN where it includes 2 phases i.e. synchronous and asynchronous phase. In initial phase sender will identify its neighbors to transmit packets and in second phase connection is established and sender will gain control of channel for delivery of packets. High delivery rate of packet is achieved and delay of the transmissions is reduced. Acknowledgements of packet will be delayed since second phase is asynchronous.

FLEXI-TP [9] is based on TDMA scheduling. Nodes wakeup in their scheduled slots for transmission of data and sleep for rest of the time. Nodes can build, modify and extend the schedule of slots based on local information available to them. It uses depth first schedule due to which buffering of packets will be reduced and communication slots are re-used by nodes which don't fall in each other's interference range. End-to-End data delivery rate is achieved while keeping memory constraints in consideration.

Life time of network is crucial in WSN due to its nature of use and complexity involved in replacing node or battery. Energy Efficient protocol is needed in WSN while routing and QOS requirements must be met. AFST [10] was proposed for reducing redundancy in network and achieves load balancing. Based on energy of node it decides whether a fusion can be performed at a given node or not. This protocol follows a tree approach for fusion of data and can be merged with designing of cluster based algorithms. [11] routing algorithm considers connectivity of remaining sensor network. It specifies importance of certain nodes whose disintegration will disrupt entire network. Importance of node is specified by Fiedler value of remaining network when a node expires. Each of nodes is associated with cost/metric for routing and proposes a keep-connect routing algorithms which use computable measures of network connectivity.

EECCR [12] suggests a m-coverage n-connectivity problem. This is based on heterogeneous sensor nodes where nodes are deployed in a given area. The algorithm does not need any location information of nodes. Nodes in each of scheduling set are activated periodically and energy balancing of nodes is done to prolong lifetime of network. Latency of packets is reduced and reliability of transmission is increased. This is mostly based on slot based approach. AsOR [13] is a unicast routing technique for multi-hop wireless sensor networks over different channels. The protocol has 3 different nodes namely frame nodes, assistant nodes and unselected nodes. Frame nodes are used to decode and forward a packet. Assistant nodes are used to provide security of un-successful transmissions. The protocol defines a value N i.e. minimum no of nodes which are required for transmission from source to destination. As a result Energy consumption of network is reduced.

The above protocols are mostly based on tree approach and require a slot based mechanism to transmit data. Scheduling of slots and varying them according to the given data will consume certain time and energy. Nodes use sleep and awake mechanism for transmission of data. When data is not available for that particular slot then the node has to remain idle and certain energy of the node is consumed.

Location based algorithm [14] was proposed for WSN where network is divided in to virtual grids. This helps us to reduce redundancy of data. Nodes are associated with GPS, but in real-time it's impractical to associate each and every node with GPS since a certain amount of overhead and energy is consumed with finding the location of node. Mobility, heterogeneity and faulty node issues have not been considered here. EBGR [15] selects its next node based on energy optimal mechanism as the relay node. The node uses RTS and CTS mechanism to route data. But protocol does not consider loss of packets during transmission.

Electing of clusters and cluster heads in WSN's is crucial since they involve a lot of energy and computation. An energy efficient and dynamic clustering protocol [16] was proposed. Based on signal strength received from neighboring node, each of individual nodes will compute probability of becoming cluster head. Certain factors like mobility of node, faulty nodes and heterogeneous nodes have not been specified here. A centralized routing algorithm (BCDCP) [17] was proposed for WSN's. This is a cluster based algorithm where each of cluster head is assigned equal no of nodes so that load-balancing is equal among cluster heads. However nodes were assumed to be immobile and base station is fixed.

REEP [18] is data centric, energy efficient, reliable routing protocol for WSN's. Packets are divided in two categories i.e. sense packet and information packets. Nodes process them based on their packet types. When processing packet, each node will verify residual energy present in node and if energy is below a given threshold status of the packet will be changed to negative and will be forwarded to next node or previous node for processing data. Other protocols such as [19], [20] explain about communication between sensor networks and actor networks. Communication between actors network will take place with help of sensor networks which are deployed in network. Sink is confined to points where energy of network can be utilized in an efficient way.

Some of other protocols are present in WSN [21], [22], [23], [24], [25], [26], [27] are energy based routing. Most of above protocols are either based on flooding, clustering, gradient or geographic based approach. Geographical approach will increase cost of network. In clustering approach inappropriate load balancing will consume energy and there is also an overhead for selecting new cluster head when old cluster head's threshold reaches a particular level. Flooding based mechanism will achieve reliability of transmission at cost of duplicate packets in to network. As a result cost associated with network is more or energy of network is over utilized in these circumstances. Hence we propose a protocol based on following factors 1) heterogeneous nodes 2) congestion 3) interference 4) mobility of the nodes 5) fault tolerant issues 6) residual energy of the nodes

Here we propose FSA-FTEER protocol which is based on finite state automata and is both fault tolerant and energy efficient. Routing algorithm finds a node-disjoint multipath where paths don't interfere with each other. Proposed protocol will consider faulty nodes and data are routed with help of multi paths which are found in network. The protocol will maintain information about neighboring nodes for routing and global topology of network is not needed. Mobility of nodes is considered and congestion is controlled based on load balancing of paths. Optimal Value of link is calculated by considering residual energy of node.

3. Proposed solution

3.1 Finite state automata

A total of 5 states are defined in FSA with respect to a node. SLEEP state specifies that the node is in power saving mode and no operations in the node are performed. A node is in SLEEP state when it's idle. ACTIVE state specifies that a node is processing data received by it or data generated because of event detection. TRANSCEIVER is a state where node is sending or receiving data. This is a state where maximum energy of the node is utilized. ERROR state specifies that node is a faulty node and it can't be used for any kind of transmission or processing of data. MOBILITY state specifies that node is moving. Mobility of the nodes can be achieved using some random way point model. States of the node are represented using a 3- bit sequence.

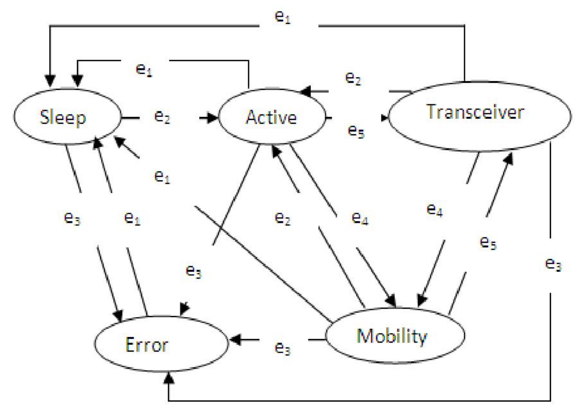

Fig.1: States of Node with transitions among them

Finite State Automata will act as a decision maker while routing is taking place. Based on parameter values which are defined in node and state in which the node is present, current node finds next best optimal node (i.e. neighbor node) for transmission of data. At a given instant of time, a node will be in a single state. Transition from one state to another is based on the type of operation performed by the node on received data. States of node are represented using a 3- bit representation. Bit representation of nodes will help to form non interfering node-disjoint multipath routes.

Table 1 Transition Table

δ	e_1	e_2	e_3	e_4	e_5
000	u	001	100	u	u
001	000	u	100	011	010
100	000	001	100	011	u
101	000	001	100	u	010
110	000	u	u	u	u

Above is the state transition table for the transition function δ. e_1 = idle, e_2 = event detected, e_3=error occurred, e_4=mobile, e_5=packet sent/received.

Deterministic Finite Automaton:-

For DFA define the set of states S = {000, 001, 010, 011, 100} and events E= $\{e_i : 1 \le i \le 5\}$. Then $\delta : S \times E \rightarrow S$ is a partial function given by the transition table. Entries labeled u are undefined.

Table 2 Bit Representation of Finite State Automata

NODE_STATE	BIT REPRESENTATION
Sleep	000
Active	001
Transceiver	010
Mobility	011
Error	100

Table 3 Parameters of node with respect to state

Parameter	Abbreviation	Description
Node Id	**NID**	Each of the nodes in the network is represented by a unique node id.
Type of Node	**TON**	Specifies type of node as network will consist of heterogeneous nodes deployed in the area.
Total Energy	**TE**	Initial energy present in node.
Residual Energy	**RE**	Remaining energy present in node.
Energy used for current Activity	**ECA**	The activity can be in-node data processing, sending receiving of data.
Threshold Energy	**TRE**	Residual energy to which node can process data or perform transmissions.
Current State	**CS**	Specifies current state of node.
Type of Packet	**TOP**	Packet can be a data packet or control Packet.
Length of Packet	**LOP**	Specifies length of packet.
Priority of Packet	**POP**	Specifies priority of packet
Path ID	**PID**	Specifies a path id of packet. This path id is stored in all nodes which a data packet traverses.
Path Group ID	**PGID**	Specifies path group id. Path group id is for, set of packets generated from same source for a particular event, where packets traverses in different paths.

3.2 Routing Algorithm

Initialize

Initialize the complete network where all nodes know their positions in terms of direction with respect to Base Station (Sink). Initialize parameters of node which are important in decision making while finding the routing paths

α_{TE} =10,000 mW

α_{TRE}=1000mW

α_{I}= 2mW

α_{EUS}=15mW/32bit

α_{EUR}= 30mW/32bit

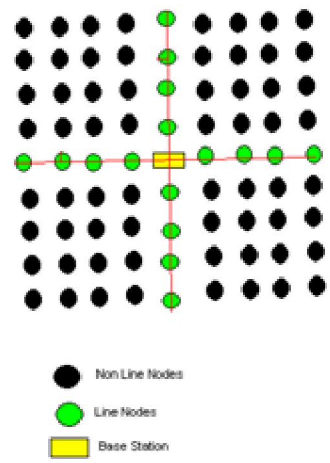

Fig.2: An Example Network

Input

Node with its parameter values at the given instant of time when the packet is ready to arrive or leave and the value of contents which are present in the packet

Output

Routing path with optimal weight to route the packets from source to destination

Steps

1: Repeat

2: Remove the Packet from Queue
Process the Packet

3: Identify neighbor nodes and send a request to the entire neighbor nodes for identifying its position with respect to Base station

4: Based on Response received from neighbor nodes calculate the probability of direction

5: Direction probability:-
Define the set of directions D as D = {N, E, W, S, NE, NW, SE, SW}
Now the probability of direction d ε D is given by

$$\Pr[d]=\frac{\sum_p 1_d(p)}{\sum_p \sum_{d' \in D} 1_{d'}(p)} \quad (1)$$

Here 'p' is the received packet and '1_x' is the indicator function in direction 'x'. The above indicator functions, for more accuracy, may be weighted with a function which is inversely proportional to euclidean distance of the node sending 'p', to the source node. This distance may be

approximated using timestamps (to be incorporated in the packet).
6: Select nodes which are in direction of max probability
7: Define F = {α_{RE}, α_{ECT}, α_{POP}, α_{QL}} where F denotes the family of parameters based on which the node calculates the optimal weight.
8: Find weight of paths from source node to neighbor node
9: $W(n_{adj})=\sum_{S \varepsilon F} R_S(S(n_{adj}))$ where n_{adj} ε $Adj(n_0)$ (2)

$W(n_{adj})$ represents the weight of adjacent node.
10: Select the node with optimal weight for transmission of Data
11: Send RTS and start a timer
12: if (CTS received before timer expired)
$n^{(1)} = Min \{W(n_{adj}) : n_{adj} \varepsilon Adj(n_0)\}$ (3)
where $n^{(1)}$ is optimal node used for transmission of data.

13: else
$n^{(2)} = Min \{W(n_{adj}) : n_{adj} \varepsilon (Adj(n_0)- \{n^{(1)}\}) \}$ (4)
where $n^{(2)}$ is optimal node used for transmission if $n^{(1)}$ is not ready to receive the data.
14: end if
15: until no more packets left in the Queue

Table 4 Family of parameters used for finding optimal node.

PARAMETER	DESCRIPTION
α_{RE}	Residual Energy of the node
α_{ECT}	Energy used for Current transmission activity
α_{POP}	Priority of Packet
α_{QL}	Queue Length Present in the Node
α_{TE}	Total energy of the node
α_{I}	Energy utilized by node when its idle
α_{EUS}	Energy used for sending data
α_{EUR}	Energy used for Receiving data

3.3 Packet format

Table 5 Structure of Message Packet

SID	DID	TOP	PID	PGID	DATA	DIRT	SEQ NO	LOP
0 6	7 13	14 15	16 18	19 21	22 53	54 56	57 62	63 68

Table 6 Description of Packet Format

CONTENTS	DESCRIPTION	NO OF BITS NEEDED FOR REPRESENTATION WITH THEIR RANGE
SID	Specifies Source ID of node which is sending packet.	7 [0,6]
DID	Specifies Destination ID of node for which packet is to be received.	7 [7,13]
TOP	Type of Packet. It can be data packet, control packet or choke packet.	2 [14,15]
PID	Specifies Path ID of packet. This path id is stored in all nodes which a data packet traverses	3 [16,18]
PGID	Specifies Path Group ID. Path group id is for, set of packets generated from same source for a particular event, where packets traverses in different	3 [19,21]
DATA	Data which is sent from source to destination.	32 [22,53]
DIRT	Specifies Direction in which packet is being sent or received.	3 [54,56]
SEQ NO	Specifies Sequential No of packet.	6 [57,62]
LOP	Length of Packet. If length of packet is large in size it's fragmented in to smaller sizes.	6 [63,68]

3.4 Numerical evaluation

Let us consider that node at position (-5, 5) has just arrived there and it needs to know its position w.r.to base station in terms of direction. It then sends a broadcast packet to all of its neighbor nodes. These neighbor nodes will inform the source node that they are in NW direction with respect to base station. The source node will now calculate the probability of direction with respect to base station

$$Pr[d]=\frac{\sum_p 1_d(p)}{\sum_p \sum_{d' \in D} 1_{d'}(p)} \quad (1)$$

Since maximum probability of the direction of the base station is NE, the source node will fix its position to be NE with respect to the base station.

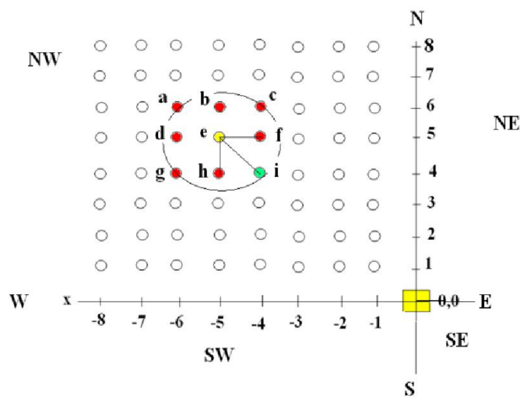

Fig.3 : Source node with other nodes and sink in co-ordinate system

n(e) is considered as source node and nodes a,b,c,d,f,g,h,i are considered as its neighbor nodes.The circle indicates the range of source node n(e).Base station is at position (0,0). Source node then needs to find next best optimal node for transmission of data. It identifies nodes n(f), n(h), n(i) as neighbor nodes for transmission of data.With ranking methodology source node needs to find optimal node for transmission.

Table 7 Nodes along with their parameter values

NODE/PARAMETER	α_{RE}	α_{ECT}	α_{POP}	α_{QL}
n(f)	80	45	1	7
n(h)	90	35	1	10
n(i)	70	40	1	5

Hence source node now finds the rank of these nodes where
n(f) = 2+3+1+2= 8
n(h)= 1+1+1+3= 6
n(i)= 3+2+1+1=7
since the node n(h) has the best ranking among all the 3 nodes its selected as the optimal node for transmission of data.

4. Conclusion

FSA-FTEER is a fault tolerant and energy efficient routing protocol. Based on finite state automata, the routing algorithm finds a node-disjoint multipath route where paths don't interfere with each other. Congestion controls is achieved with help of load balancing and choke packets. Faulty nodes and mobility of nodes in network are considered while routing the packets. Optimal Value of link is calculated by ranking method and it also takes residual energy of node in to account. Protocol is both fault tolerant and energy efficient, even when the base station is mobile. In our future work we try to implement a test bed of protocol to verify the simulation results in a real-time environment.

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