Asian Journal of Information Technology 15 (8): 1289-1296, 2016
ISSN: 1682-3915

A Novel Fuzzy Integrated Fault-Tolerant and Energy-Efficient Routing Protocol for Wireless Sensor Network

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Abstract: For a long time, Multi-hop Wireless Sensor Network (WSN) communication continuous to be the predominant network for several applications. Such systems are often prone to link or node failures due to various factors and ultimately increases contention, significant overheads, etc. Moreover, deployed nodes in the network are energy constraint and thus utilization of limited energy resource with reliable routing always poses research challenges. Some of the traditional routing protocols like DSR and AODV and their recent advanced variants expose approximate negative tradeoff between fault-tolerance and energy efficient routing. In this study, a novel Fuzzy Integrated Fault-Tolerant and Energy-Efficient Routing Protocol (FI-FERP) is proposed. We design and apply fuzzy rule matrix to determine multi-optimal routing paths between source and destination along with energy concerned interesting patterns. Since the basic concept of fuzzy logic manages to provide a clear, logical outcome, its rule-set consolidation on decision-making sector plays a vital role in the discovery of optimal routing paths and provides high-quality alternative paths in case of link/node failures. Consequently, all the participating intermediate nodes along the routing path are self-evaluated against possible hardware faults such as transceiver and microcontroller faults. Simulation solvents of FI-FERP have shown betterments in packet delivery ratio against node/link failure, decreases the control packet overheads with optimal energy consumption.

Key words: WSN, reactive routing, link failure, fuzzification, defuzzification, multi-optimal routing, packet delivery ratio

INTRODUCTION

The WSN is an inexpensive, emblematic network to collaborate with any other advanced technologies. It can be simply defined as the finite group of motes which is the combination of sensing, processing, storing modules with powerful features such as continuous monitoring, acting as a perfect communicant to exchange information for an on-demand decision making. Such type of sensor motes in the network are simple and realistic to expel many real time problems but often prone to failures due to their deployment strategies in harsh conditions and resource limitation factors such as bounded battery power, limited computational capability, unreliable wireless link, etc. In marking to those limitation factors, it's hard to design energy efficient and fault tolerant routing protocol. Though some recent research activities, in concerned to such routing protocol have been proposed, none has divulged to follow simple computations to route the data's. As referred, most existing WSN routing protocols (Nasipuri et al., 2001; Perkins and Royer, 1999; Royer and Toh, 1999; Xue and Nahrstedt, 2004; Stojmenovic and Lin, 2001) are associated with only single path scheme. There is a mandatory trade-off between computation process and discovery of multiple routes. Furthermore, at the time of node or link failures, identifying and choosing an appropriate alternative path from multiple choice is a vague decision process. So, it is necessary to incorporate inbuilt-logical ideas. Thus, integration of Fuzzy logic concept is found to be a better mode of such logical thinking and to take crisp decision outcome under the ambiguous situation. The fuzzy paradigm follows the low-cost computation procedures, which directs the integrated system to obtain an optimum solution (Table 1).

The main thematic of this study is to identify multi-optimal routing path using fuzzy logic concept and to self-evaluate each intermediate nodes against transceiver and microcontroller fault. Several reviewed article (Wang *et al.*, 2005; Rea and Pesch, 2004; Song

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Table 1: Abbreviations and acronyms

Abbrivation	Acronyms
WSN	Wireless Sensor Network
DSR	Dynamic Source Routing
AODV	Ad-hoc On-Demand Vector
FI-FERP	Fuzzy Integrated Fault-Tolerant and Energy-Efficient Routing Protocol
FIFO	first-In-First-Out
QoS	Quality of Service
RSSI	Received Signal Strength Indicator
RREQ	Route Request
RREP	Route Reply
REER	Route Error
HC	Hop-Count
amp	Amplifier
MoM	Mean of Maximum
NF	Node Fault
J	Joules
pJ	pico-Joule
J	micro-Joule
Mbps	Mega-bits per second
Kbps	Kilo-bits per second
m	meter

and Fang, 2006; Jin *et al*., 2006; Su *et al*., 2008; NiaziTorshiz *et al*., 2008; Fahad and Ali, 2010; Zuo *et al*., 2010; Ortiz *et al*., 2011; Dehyadegari *et al*., 2011), regarding fuzzy based WSN routing protocol, fails to evaluate both routing path as well as hardware units with low computational cost. The proposed scheme follows the basic DSR procedure like route request, route reply and route error. After obtaining several RREQ paths, the destination node identifies the features of routing path using fuzzy logic metrics. Here, the participation of faulty nodes and control overheads of RREQ packets are limited by self-evaluation procedure of intermediate nodes along the path.

MATERIALS AND METHODS

Most of the present traditional and advanced reactive routing protocols lack significance role in attaining maximum reliability, especially during route failures. The fuzzy logic system proposed by Wang *et al.* (2005) deals to improvise routing policies and its performance dynamically. Though, this approach under high mobility conditions dynamically adapts and stabilizes the parametric values has not succeeded in optimizing energy consumption.

To minimize control overheads and packet latency (Rea and Pesch, 2004) formalizes multi-metric routing protocol by three metrics namely link strength, remaining energy available at a link vertex and hop counts. Using fuzzy logic approach node level limited capacity path cache is optimized to rule-out the records of low-quality links. This protocol poses some of the demerits such as deconcentration on both route and time cost, utilization of FIFO policy to remove old entries in the cache.

The QoS-aware routing based on fuzzy conceptions by Song and Fang (2006) focused on improvisation of average throughput and delay routing. It mainly resolves traffic management problems but as the node density increases, it eventually affects link quality and degrades the performance.

In integration of fuzzy logic provides security provision for the delivery of routing packets with a typical strategy to determine the most secure routes (Jin *et al*., 2006). It consumes more time on route discovery phase than traditional protocols like AODV. Moreover, when the node density increases in the network, there is a notable gradual decrease in security level.

Modified fuzzy based AODV is proposed by Su *et al.* (2008) where measured multi-criterion parameters are applied to determine the optimal routes. The performance of this approach exposes betterment especially regarding high mobility, packet delivery ratio and stable route acquisition. At a certain level of node's motion (approximately 4-6 m sec^{-1}), the performance rate of delivering packets from source to destination are found similar with traditional AODV.

In utilization of minimum bandwidth along with optimal energy consumption is performed by incorporating fuzzy logic concept with AODV (Torshiz *et al*., 2008). Though the proposed approach selects the most optimal route and consumes very less bandwidth, fails to decrease the time delay for calculations, which intern increases transmission latency whenever network density increases.

The majority of the reactive routing protocols have not focused on delay characteristics during packet transmission. Focusing on such characteristics not only improvise packet delivery proportion but also maintains high-end stabilized and sustainable network operations. Thus, to determine optimal route, the proposed protocol appends delay period and hop count of each path as the metric input value to the fuzzy rule base (Fahad and Ali, 2010).

Only very few protocol concern regarding route break tolerance and their alternate solvents. One such proposed protocol in depicts a unique solution for route breaks (Zuo *et al*., 2010). The number of hops and route-lifetime are considered as vital input parameters in the fuzzy logic mechanism as to transmit data through best-stabilized route. The possible outcome of the fuzzy aided proficiency system mitigates the path break which further yields meliorated network throughput.

In ZigBee based mesh network, proposed protocol depicted by Ortiz and Rayo (2011) reduce energy consumption, collision, end-to-end delay and increases the network lifetime by incorporating fuzzy logic concept. The proposed work considers three input parameters namely hop count, Remaining energy level and RSSI to choose the better active node which would be the part of the routing path. When, adopting the same procedures in case of a large network, there is a high possibility of obtaining undesirable routes.

In Fuzzy logic based an adaptive routing algorithm for an on-chip network is proposed (Dehyadegari *et al*., 2011). In which finite empty spaces of each neighbor buffer and the previous packet waiting time are used as input parameters to manage the traffic during high congestion period.

From the literature summary, it has been clearly experienced that none of the proposed schemes has strongly imposed effective research on fault tolerance domain in the aspects of data transmission as well as hardware level of the node. Since, the influence of these aspects contributes high-performance qualities of the network, our nominated scheme imparts the idea of collaborating fuzzy logic concept with reactive routing procedures to overcome the uncertainties of network negative impacts.

Fi-FERP design: In this discussion study, the overall network design theory and parameters are briefly elaborated.

System model: Let, N be the set of n sensor nodes, N = {1, 2, 3, ..., n}, which is stationary and battery powered deployed in a supervising terrain. The proposed WSN is represented as well-connected graph G(N, L) where N is the set of a total number of sensor nodes and L is the total number of communicating edges between the nodes. Our system model is assumed to pose: static, homogeneous sensor nodes, finite energy source with 5 joules of initial energy, to choose optimal path, any destination node, d is capable of imposing proposed fuzzy logic standard procedures, Each wireless link between the nodes is presumed to be duplex.

Energy model: The formulation source of our energy model is entirely referred from (Chanak and Banerjee, 2016). In which energy consumption of each nth sensor node per transmission is constituted as in Eq. 1 where L_t is the energy consumption of transmission electronics. The R_{d1} and R_{d2} represent the amount of energy required for the amp in free space and the multi-path model. Further, r and S_n denotes the transmission range and transmitting message size of nth sensor node, respectively:

$$ec_t = \begin{cases} ((L)_t + R_{d1} r^2)\, Sn, r < d_0 \\ ((L)_t + R_{d2} r^4)\, Sn, r \geq d_0 \end{cases} \quad (1)$$

Equation 2 depicts the energy consumption at the receiver side where L_r refers to the energy consumption of receiver electronics and similarly, S_n represents receiving message size of the nth sensor node:

$$ec_r = (L_r S_n) \quad (2)$$

Scheme rationale: The FI-FERP scheme rationale is comprised of two phases, namely self-examining the hardware circuitry conditions of each node against unpredicted faults during route request phase and finding optimal routing paths using fuzzy logic concept. Since the proposed protocol follows some of the standard procedures of DSR, its clinical arrangements before data transmission like routing request, routing reply, routing error are imparted to our schema. Few enhanced procedures are appended to the basic work nature of DSR to support fault tolerant and energy efficient routing.

Phase-I; self-examination of hardware units: After network initialization, one or more events are generated by n number of source nodes. Before sending data packets, each source node has to gain substantial routing knowledge. Thus, such type of nodes dissipates RREQ control packets to its neighbors to find the routing path towards the destination. Once the intermediate nodes acquire RREQ, self-examines its energy level with the fixed threshold value. The network analyzer or administrator can set and configure the threshold value according to the network requirements. All the intermediate nodes are eligible to forward the acquired RREQ, only if its remaining energy level is found to be higher than the threshold value. Thus, the possibilities of RREQ control packet overheads are restricted. Equation 3 depicts the route request forwarding function of intermediate nodes where $RE_n(t)$ represents the remaining energy level of node n, at time t and τ denotes the fixed threshold value. Moreover, the value 1 implies the eligibility status for forwarding and 0 indicates ineligibility condition as well as the possibility of a battery fault. This self-examining phase, point out the critical factor of preventing the node from possible battery failures during data transmission:

$$f(n_{REEEQ}) = \begin{cases} 1, & RE_n > \tau \\ 0, & RE_n \leq \tau \end{cases} \quad (3)$$

After battery inspection, every node examines its receiver, transmitter and microcontroller units. At any

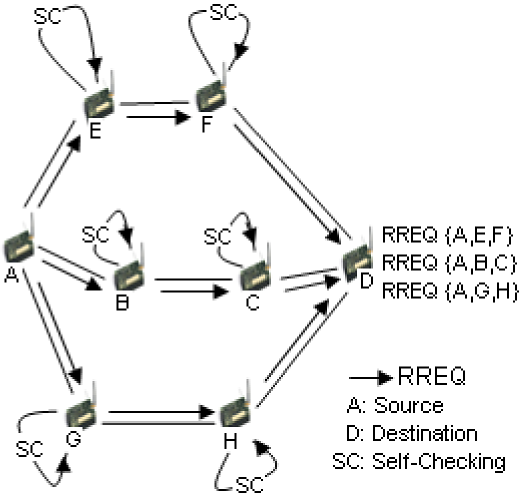

Fig. 1: Working mehanism of phase-I

cost, all units must be tested without any complex computations and much time delay. Thus, beacon signals are utilized for each trial especially for its low processing and energy cost for generating, transmitting which is less than the data signal. Here, the intermediate nodes generate three consecutive beacon signals and transmit to itself. If it succeeds in generating the beacon signals in a precise time-span then its microcontroller unit is found to be in a fault-free condition. Additionally, if it succeeds in transmitting and receiving the signal then its transceiver units are also considered to be in a fault-free state. So, those nodes which pass all these self-examinations are eligible to forward the received RREQ towards the destination. A simple diagrammatic representation in Fig. 1 depicts the practical nature of phase-I rationale.

Phase-II: finding multi-optimal routing paths: To obtain the accurate optimized output from an imperceptible and ambiguous set of input data's, utilization of fuzzy logic is a most beneficial option than imparting other energy consuming and excessive computational techniques. Moreover, its logical influential factors over uncertainty situations produce precise, optimized, inexpensive computational outputs. Here in phase-II, it is intricately described the role of the destination node in choosing a clear multi-optimal routing path from acquired RREQ paths. In our research, incorporated fuzzy rule base system plays a decisive role in identifying the optimal paths based on relevant linguistic variables. A standard fuzzy system consists of three stages: Fuzzifier, Fuzzy Inference Engine and Defuzzifier.

Fuzzifier: This is the first stage which maps the crisp input values of the system to the corresponding fuzzy set.

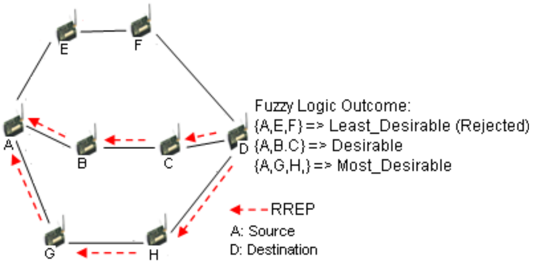

Fig. 2: Working mehanism of phase-II

Table 2:

Membership function (Input)	Low (L)	Medium (M)	High (H)
RE (J)	0.0-1.1	2.5-3.5	>4.0
HC (counts)	0-1	2-3	>4.0

Inference Engine: This second level consists of serious of IF-THEN rules that parallelly evaluates the fuzzified input with the linguistic variables.

Defuzzifier: After the unification of all rules, this stage performs transformation of the consequent fuzzy set into a single crisp output. This process of defuzzification is handled through several conventional techniques like centroid of the area, mean of maximum, weighted average, etc. Major theoretical facets of fuzzy logic are referred from Bonissone (1980) and Nguyen (1995).

After the self-examination in phase-I, along with RE each intermediate nodes rebroadcast the RREQs similar to DSR. Thus for specified time interval, each destination node is supposed to receive, n number of RREQ paths with their aggregated RE and HC. After the acquisition of n number of RREQs, destination node imparted with fuzzy logic determines the path feature based on aggregated RE and HC of each path. Here, the path elements are categorized by three prioritized features namely most_desirable, desirable and least_desirable.

- Most_desirable: first choice of selectable route for data transmission
- Desirable: it's a preferred path for data transmission next to the most desirable option
- Least_desirable: unfavorable path to route data packets

This mode of selection is based on membership functions and framed fuzzy rule base which is defined in Table 2 and 3, respectively. On determining the path feature for each acquired RREQ packets from the source node, the destination node prefers to send RREP packets only to those route paths which possess most_desirable and desirable path features. This has been diagrammatically represented in Fig. 2.

Table 3: Mamdani model FIS rule base

Rule No.	Nodes	RE	Nodes	HC	Nodes	Path_Feature
R1	IF	L	AND	L	THEN	Desirable
R2	IF	L	AND	M	THEN	Least_desirable
R3	IF	L	AND	H	THEN	Least_desirable
R4	IF	M	AND	L	THEN	Most_ desirable
R5	IF	M	AND	M	THEN	Desirable
R6	IF	M	AND	H	THEN	Least_desirable
R7	IF	H	AND	L	THEN	Most_desirable
R8	IF	H	AND	M	THEN	Desirable
R9	IF	H	AND	H	THEN	Least_desirable

Thus, the source node obtains multi-path options to transmit the data packets. During critical link/node failures, RERR packet is sent to the node of origin. In such cases, availability of multi-route option provides maximum tolerance and ensures the completion of data transmission between source and destination.

Mathematical formulation of fuzzification strategy: Here, the two input variables namely RE and HC of the fuzzy system are briefly defined. To reduce computational complexity, we applied trapezoidal shaped membership function. The three labels low, medium, high represent the linguistic values of RE and are defined as follows:

$$RE_{L(X)} = \begin{cases} 1, & X < 1.1 \\ \frac{(2.5-X)}{0} 5, & X \le 2.5 \\ 0, & 2.5 \le X \end{cases} \tag{4}$$

$$RE_{M(X)} = \begin{cases} \frac{X-1.1}{0} & 0, \ X < 1.1 \\ & 5, \ 1.1 \le X \le 2.5 \\ \frac{3.5-X}{0} & 1, \ 2.5 \le X \le 2.5 \\ & 0, \ 4 \le X \end{cases} \tag{5}$$

$$RE_{H(X)} = \begin{cases} 0, & X < 3.5 \\ \frac{(X-3.5)}{0} \ 5, & 3.5 \le X \le 4 \\ 0, & 4 \le X \end{cases} \tag{6}$$

Equation 4-6 defines different boundary conditions of the input variable RE. Fixing the boundary specifications is purely dependent on parametric values of deployed environment and application. Thus, for the lower bound of RE is fixed at 1.1, the middle bounds are fixed as 2.5, 3.5 and finally upper limit is set to >4 which is distinctly depicted in Fig. 3. In a similar manner, with the same linguistic values specified to RE are also specified for second input variable HC. Equation 7-9 represents the boundary limitation of HC where the lower limit is fixed as 1, the middle bounds are 2 and 3 and the upper bound is >4 which is picturized in Fig. 4:

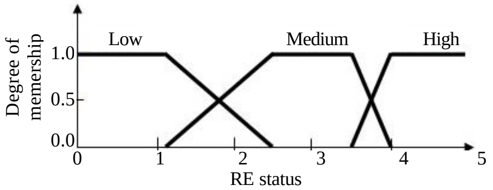

Fig. 3: Membership functions of RE

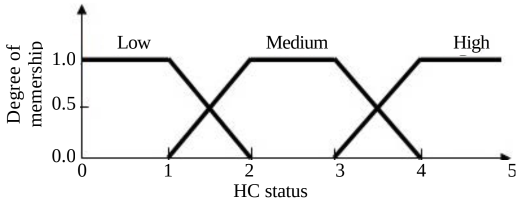

Fig. 4: Membership functions of HC

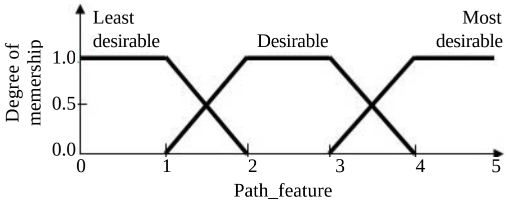

Fig. 5: Membership functions of output variable

$$HC\_L(X) = \begin{cases} 1, & X < 1.1 \\ \frac{(2-X)}{0.5}, & 1 \le X \le 2 \\ 0, & 2 \le X \end{cases} \tag{7}$$

$$HC\_M(X) = \begin{cases} \frac{X-1}{0} & 0, \ X < 1 \\ & 1, \ 1 \le X \le 2 \\ \frac{4-X}{0} & 1, \ 2 \le X \le 3 \\ & 3 \le X \le 4 \end{cases} \tag{8}$$

$$HC\_H(X) = \begin{cases} 0, & 3 < X \\ \frac{(X-3)}{0.5}, & 3 \le X \le 4 \\ 1 & 4 \le X \end{cases} \tag{9}$$

Figure 5 depicts the fuzzy output variable that consists of three membership values which represent the path feature. For both RE and HC, the universe of disclosure is [0, 5] and the distinguished boundary levels are stated regarding joules and counts respectively. We utilized Mamdani model in the inference system and MoM defuzzification (Saade and Diab, 2000) method to obtain the crisp output. A sample model of MoM defuzzification is briefed in Fig. 6.

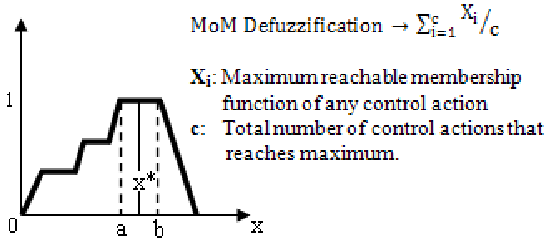

Fig. 6: MoM defuzzification process

RESULTS AND DISCUSSION

Implementation scenario: The proposed protocol is compared with the conventional DSR protocol and the performance has been assessed using NS2 simulator with experimental parametric values of interest specified in Table 4. In the proposed protocol, each intermediate node needs extra-bit space to append its RE along with RREQ and likewise destination node also demands additional bit space to add the information of path preference status during RREP to source node. The RERR follows the same semantics and formats of DSR.

Performance evaluation: In this study, the experiments are carried out based on two perceptions.

- Packet delivery ratio vs percentage of node/link faults
- Energy consumption of control packets vs ith Events

The performance metrics of those two aspects are defined as:

Packet delivery ratio: Ratio of the number of packets received by the destination node to the number of packets sent by the source node (Ahmed, 2015).

Percentage of NF: The ratio of the number of hardware faults of sensor nodes to the number of fault-free sensor nodes in the network (Chanak and Banerjee, 2016).

Energy consumption of control packets: Energy spent per event by each intermediate node in receiving and sending RREQ and RREP control packets.

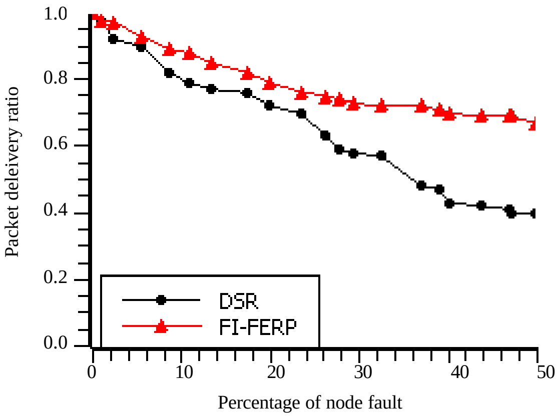

Fig. 7: Simulation result for PDR Vs Percentage of NF

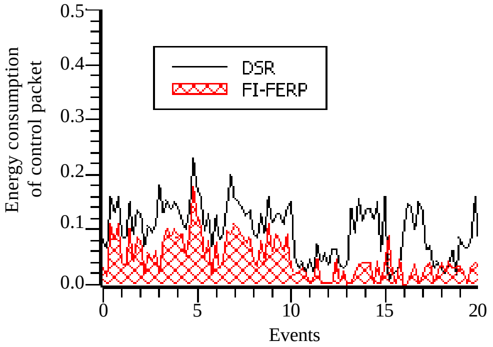

Fig. 8: Simulation result for energy consumption of control packets vs events

Table 4: Simulation specifications

Parameters types	Values Application	 Network topology	 Radio model
Simulation time (T)	20000 sec	-	-
Bandwidth	1 Mbps	-	-
Data rate	512 Kbps	-	-
Beacon data size	10 bits	-	-
Energy threshold	10%	-	-
Topology size	-	1000×1000 m	-
Node type	-	Homogenous	-
No. of nodes	-	50	-
Channel	-	Wireless	-
Channel_Type	-	Bidirectional	-
Energy model	-	-	Battery
Initial nodes energy	-	-	5.0 J
Transmit amplifier	-	-	100 pJ/bit m^{-2}
Transmitter electronics	-	-	4.28 μJ/bit
Receiver electronics	-	-	2.36 μJ/bit
Idle mode	-	-	2.36 μJ sec^{-1}
Sleep power	-	-	0.00001J sec^{-1}

To some extent, the proposed protocol follows similar working mechanism of DSR. In concerned to energy saving and fault tolerance routing, few modifications has been adapted to DSR. The simulation results shown in Fig. 7 depict the comparison of packet delivery ratio of both FI-FERP and DSR protocols. It has been observed that FI-FERP showcases better packet delivery ratio than DSR. This betterment is one of the distinctive features of proposed scheme because whenever a node or route failure occurs, the source node gears-up to proceed with next choice of a preferred path that has been identified and provided by destination node using fuzzy logic conceptions. This type of multi-optional routing not only ensures the completion of entire events between source-destination pair but also guarantees the confidence of acquiring maximum packets delivered. Fig. 8 depicts perfective evidence to optimal energy

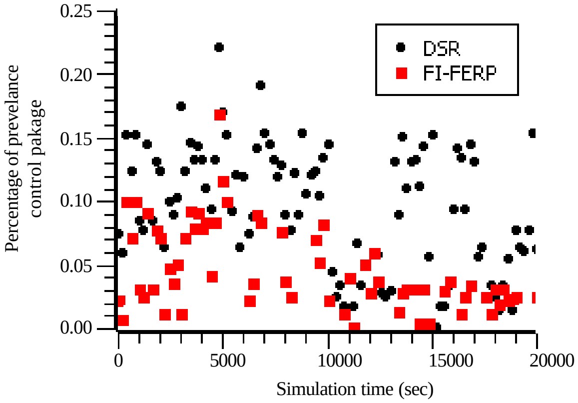

Fig. 9: Percentage of prevalence control packets vs simulation time

expenditure strategy of proposed protocol. Based on the path identification outcome of fuzzy logic, destination node limits its replying formalities to least_desirable paths. Here, it is nearly possible since the destination node limits the dissipation of RREP packets to all RREQ paths of the source node. Thus, the participation of intermediate node along the least_desirable paths is restricted. By this way energy expenditure of unwanted involvement of few nodes and unnecessary dissipation of RREP is controlled. This way of restricting RREP dissipation further minimizes its overhead in the network and the overall overheads of control packets during entire simulation periods is depicted in Fig. 9.

CONCLUSION

As aforementioned, the main thematic of this study is entirely focused on tolerating the different hardware unit faults of sensor nodes and maintaining the routine on-demand communication between the nodes. So, this special tolerance ensures the high packet delivery ratio and the process of self-checking the RE level of intermediate nodes, minimize the RREQ packet overheads. Also, integration of fuzzy logic concept at the destination node avoids reply to non-optimal paths which further minimizes the RREP packet costs in the network. The self-checking of RE at each intermediate nodes prevents its participation in effective communication since such kind of battery dependent nodes always prone to the possible chance of energy depletion. The only demerit of nonparticipation of such nodes during communication flow may slightly reduce the network throughput. Apart from that, our simulation results of proposed protocol dominate the conventional DSR in various aspects like providing low control overheads especially for control packets, optimal energy consumption and ensuring higher packet delivery ratio.

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