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**ABSTRACT**

In the present era, rapid transits are one of the most affordable means of public transport with various useful integrated application systems. The majority of the integrated applications are deployed in concern over safety and precautionary measures against the worst side-effects of unfortunate emergencies. For such cases, high-end reliable and autonomous systems provide possible positive solutions. Wireless Sensor Network is one of the suitable choices for rapid transit applications to gain positive results with inexpensive implementation cost. However, managing few network consequences like fault tolerance, energy balancing and routing critical informative packets are considered to be the challenging task due to their limited resource usage restriction. In this paper, a novel fuzzy logic-based fault tolerance and instant synchronized routing technique have been proposed specifically for the rapid transit system. On utilizing the fuzzy logic concepts, most of the computational complexities and uncertainties of the system is reduced. The central thematic of the proposed design is concerned over the synchronized routing and permanent faults which abruptly depicts the non-functional nature of the sensor nodes during normal operations. Moreover, our proposed simulation outcomes proved to be improvised evidence on obtaining maximum packet delivery ratio which tends to handle an emergency situation in the compartments of rapid transits.

## 1. Introduction

Now-a-days RTS turned to be most efficacious transit system all around the world. Due to the fastest mode of transportation, the expected minimum guarantee benchmark on passengers safety during emergency situations like derailing or any unfortunate mishap are not standardized. Some of the deployment of many intelligent applications within the compartments ensures the reduction of causalities/injuries, but still requires in-depth advancements concerning reliable communication and fast forwarding of critical messages with least computational cost. As to deal with the requirements as mentioned above, WSN [1] is a suitable option which is capable of continuous monitoring of environmental aspects and sharing the sensed data using the group of autonomous sensors.

Compared to any wired network, WSN is found to be cheap, flexible in deployment, most favourable to deal with the outputs of environmental impacts and easy to incorporate with other technologies. Though the adaptation of WSN in RTS [2] improvises the safety measures, there is no negative gap to gaina clear decision from uncertainties. Incorporating fuzzy logic concepts in WSN applications provide an intelligent autonomous decision-making privilege and stabilize the control systems during risky situations, especially on emergency cases.

The primary thematic of this paper is to deal with the permanent faults and synchronized routing in WSN, which plays the vital role during unanticipated emergencies of RTS (mishap, firing accidents in interior cabins, etc.). Our work of addressing routing synchronization [3,4] not only avoids the collision but also imparts effectual transmissions of the climacteric signal to controller/commanding node. Using fuzzy logic concepts, our proposed system provides maximum fault-tolerance capability and packet delivery ratio in the event of packet routing.

Forthcoming discussions and elaborate analysis of this research article are framed as follows. Section 2 delineates the traditional and recent advancements in fuzzy-based WSN routing protocols and their goal-directed functionalities. Section 3 dilates the three phases of proposed work out of four, which provides brief explanation of integrated fuzzy logic [5] concepts. Section 4 elaborates the fourth aspect of the proposed approach. Section 5 deals with the discussions of simulation results, circumstance and elucidation of proposed work. Section 5 summarizes the conclusions and future enhancements.

## 2. Related work

Before elaborating and understanding the significance of the proposed work, most of the modern and conventional fuzzy-based WSN protocols are widely discussed in this section. Some of the traditional and enhanced routing protocols lack grandness role on achieving maximal reliability, particularly during mission critical event handling. The proposed article from [6] insinuated multimetric routing concept by using link strength, hop count and remaining energy among the link vertices. Though this approach minimizes the control overhead and packet latent period, failed to focus on the reduction of route cost and timing cost. Moreover, it has neglected to concentrate on proper utilization of FIFO policy to evacuate the past entries in the cache.

From the article [7], the incorporation of fuzzy logic offers high-end security provision for routing the packets with a unique scheme which determines the optimum secure routes. Moreover, when compared to other traditional routing protocols, it consumes extra timing segment on route discovery phase.

The fuzzy-based incorporated work logic in [8] addresses the performance of improvising the routing capability based on predefined policies dynamically. Despite dynamic adapting and stabilizing the parametric evaluates under high mobility conditions, this approach has not delivered the goods especially in consuming optimal energy.

In [9], QoS-aware routing which is based on fuzzy concepts is entirely concentrated on resolving traffic management problems to obtain optimal average throughput and end-to-end delay. In this work, it has been found that as the node density rises, the quality of link fades, and there is a gradual degradation in the performance.

Most of the recent fuzzy-based routing protocols have not addressed the facts of delay features at transmission packet level. Addressing such problem will provide special provisions to carry out sustainable and stabilized network operations. Hence in [10] to manage notable packet delivery proportions and optimal route, the hop count of each and every path and delay period are taken into account as the input metric value in fuzzy rule frame.

In [11] using fuzzy logic concept, an evaluated multi-criterion parametric quantities are imposed to determine the best routes. The operational execution of this proposal discloses the major improvement regarding packet delivery ratio, stable path attainment, particularly during high mobility conditions. Beside the betterments, at the node motion level between 4 and 6 m/s, the performance of packet delivery rate degrades.

The proposed facts of [12] expose the contribution of integrating fuzzy concepts regarding utilization of minimum bandwidth and consuming less energy.

Only at low-density level the network gains maximum yields by proper utilization of bandwidth and optimal route. As the node density increase's, the rate of bandwidth consumption increase's along with the time delay calculation which ultimately leads to the increase of transmission latency.

Providing a justified unique solvent for path-breaking tolerance is considered to be one of the biggest problems. In recent days only very few research articles have been inducted in such areas. One such kind of approach in [13] expresses a typical solution for tolerating unexpected route breaks. Here the life expectancy of route and hop-count are applied as input parameters for fuzzy processing to forward data packets through best route. The obtained outcome of this fuzzy assisted mechanism extenuates the route break which affords ameliorated network QoS.

Some research article uses fuzzy logic concepts to manage the traffic in peak congestion period. One such approach in [14] is proposed based on an adaptive routing algorithm, especially for an on-chip network. In these proposal only limited empty spaces of every neighbour buffer and the previous packet waiting time is utilized as input parameters.

In [15], WSN along with traditional wireless technology namely ZigBee-based mesh network incorporates fuzzy logic concepts which gain the result of reduced energy consumption, transmission latency and collision. All this positive resultant increases the network lifetime. In this approach RSSI, the number of hop counts and remaining energy level of the node are considered to route the data packets among the active nodes. Though the implementing results in small dense network obtain notable positive consequence, has the high possible chance to encounter undesirable routing paths in the vast network.

From the literature compendious and evidentiary, it has been clearly exposed that none of the research work has combinedly failed to focus on both routing fault-tolerance and synchronization, which has vital influence over data transmission to controller/commanding node in emergency conditions. Thus, our idea of integrating WSN and FL concepts for RTS, which are often prone to emergencies situations, has high influential and benchmark contributions to overcome node-level permanent faults and unreliable data transmissions.

## 3. Proposed work

In this section, the details of fuzzy-based fault-tolerant and instant synchronization technique is discussed. To understand the discussion, the relevant abbreviations and acronyms are elaborated in Table 1 for future references. For implementing the nominated work, we considered the primary network parameters from the prototype model of S70 Low-Floor Light Rail Vehicle from

**Table 1.** Abbreviations and acronyms.

| WSN | Wireless Sensor Network | TDMA | Time Division Multiple Access |
|---|---|---|---|
| RTS | Rapid Transit System | TS | Time Stamp |
| FIFO | First-In First-Out | CT | Critical Time |
| QoS | Quality of Service | BL | Battery Level |
| FL | Fuzzy Logic | D | Distance |
| $s_r$ | $r^{th}$ Sensor Node | MoM | Mean of Maximum |
| CN | Controller/Commanding Node | MF_NN | Most Favoured NN |
| NN | Neighbour Node | F_NN | Favoured NN |
| $DC_p(CN)$ | Deployed Coordinate point of CN | LF_NN | Least Favoured NN |
| $DC_p(NN)$ | Deployed Coordinate point of NN | m/s | metre per second |
| Amp | Amplifier | s | seconds |
| AODV | Ah-hoc On-demand Distance Vector | $T_x$ | Transmission Range |
| DSR | Dynamic Source Routing | J | Joules |
| OLSR | Optimized Link State Routing | μJ | Micro-joule |
| Ack | Acknowledgment | pJ | Pico-joule |

Siemens [16]. Most of the necessary system parameters are briefly elaborated in Section 4. The entire proposed system comprises four phases.

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**Phase-I: Gaining Knowledge on $DC_p(CN)$ and $DC_p(NN)$**

Input: $s_r$, $DC_p(s_r)$, $DC_p(NN)$, $DC_p(CN)$
Output: $s_r$ gains knowledge on $DC_p(CN)$ and $DC_p(NN)$

FOR $k^{th}$ deployed area Do
∀: $s_r$ Do
    CN broadcast its $(X_i, Y_j, Z_k)_{CN}$
∀: $NN \in T_x(s_r)$ Do
    $s_r$, NN exchange $(X_i, Y_j, Z_k)s_r$
END FOR

---

In phase-I, after the deployment of the whole network, it's mandatory to obtain the input parameters for fuzzy processing. Here, both remaining battery level and the distance between the *NN* and *CN* are considered as input parameters to determine the best NN to route packets. Since the motion capability of the network system is static, which is controlled by a single controller/commanding node, it's crucial to gain knowledge about its deployed coordinate by other sensor nodes in the network. Thus, *CN* broadcast its deployed coordinate points $(X_i, Y_j, Z_k)_{CN}$ to all other nodes in the network. Similarly, each and every sensor nodes within their transmission range exchanges their coordinates $(X_i, Y_j, Z_k)s_r$ with *NN*. Upon receiving the *NN* coordinates, the $s_r$ can able to derive the distance (*D*) from each of its *NN* to *CN*. As a result, each node is well aware of the distance of its *NN* to *CN*. Equation (1) represents the formulation to deduce distance between *NN* and *CN* is as

$$D_{NN,CN} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{1}$$

In phase-II, if any events get triggered, the corresponding source node broadcast a beacon signal to its *NN* to acquire the current remaining battery level.

After obtaining the *BL* of each of its *NN*, source node runs the fuzzy logic process with two parametric inputs that are *BL* and *D*. This fuzzy-based process fulfils the task of classifying *NN* between best, better

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**Phase-II: Gaining Knowledge on BL of NN**

Input: *New Event*
Output: $s_r$ gains knowledge on BL of NN

FOR *New Event* Do
∀: *NN* Do
$s_r$ sends $Event_{Sig}$
    Upon receiving $Event_{Sig}$
NN  sends its current *BL* to $s_r$
$s_r$  runs *FL* process
END FOR

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and worst case to route through. Moreover, it provides multiple options to forward data packets under any crisis. For example, if one possible *NN* fails to forward the packets due to permanent faults, the sender gets another identified option to carry over the task. The classification of *NN* is affiliated with three different subprocesses namely fuzzification, evaluation and defuzzification.

### 3.1. Fuzzification and evaluation

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**Phase-III: Finding Multi-Optimal Routing NN**

Input: *BL and $DC_p(NN)$*
Output: *Multi-optional optimal NN*

FOR *New Event* Do
∀: $s_r$ Do
    Fuzzify *BL,D*;
    Evaluate fuzzified input;
Defuzzify the evaluated input;
END FOR

---

The phase-III commence with the fuzzification process. Transformation of the crisp input value into fuzzy value is known as fuzzification. To reduce computational complexity and to map input values to the corresponding fuzzy set, we opted trapezoidal shaped membership function with three linguistic variables: Low (*L*), Moderate (*M*) and High (*H*). These variables are common to both BL and D, which are defined in Table 2.

The fuzzification process of both *BL* and *D* using trapezoidal shaped membership function are mathematically specified from Equations (2) to (4) and

**Table 2.** Membership function.

| Input | Membership function | | |
| | Low (L) | Moderate (M) | High (H) |
|---|---|---|---|
| BL (in joules) | 0.0–1.1 | 2.5–3.5 | 4.0–5.0 |
| D (in metres) | 0–10 | 20–35 | 40–50 |
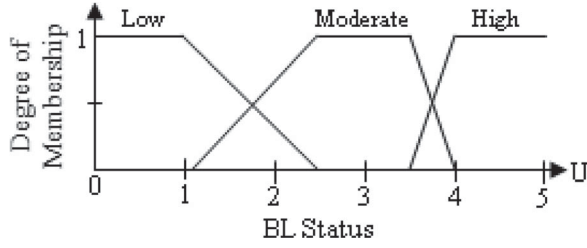


**Figure 1.** Membership function of *BL*.
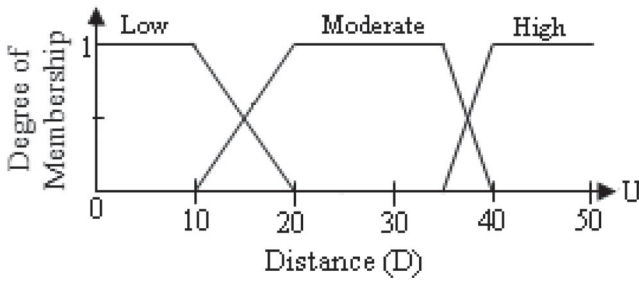


**Figure 2.** Membership function of *D*.

diagrammatically depicted in Figures 1 and 2.

$$BL\_L(U) = \begin{cases} 1, & U < 1.1 \\ \frac{(2.5 - U)}{0.5}, & 1.1 \leq U \leq 2.5 \\ 0, & 2.5 \leq U \end{cases} \quad (2)$$

$$BL\_M(U) = \begin{cases} 0, & U < 1.1 \\ \frac{(U - 1.1)}{0.5}, & 1.1 \leq U \leq 2.5 \\ 1, & 2.5 \leq U \leq 3.5 \\ \frac{(3.5 - U)}{0.5}, & 3.5 \leq U \leq 4 \\ 0, & 4 \leq U \end{cases} \quad (3)$$

$$BL\_H(U) = \begin{cases} 0, & U < 3.5 \\ \frac{(U - 3.5)}{0.5}, & 3.5 \leq U \leq 4 \\ 1, & 4 \leq U \leq 5 \end{cases} \quad (4)$$

The Membership function of *BL* is defined in Equations (2)–(4) with distinguished boundary conditions. The Equation (2) delimits the lower bound of *BL* at 1.1, (3) specifies the middle bound as 2.5 and 3.5 and (4) defines the upper limit of *BL*, which is fixed as 4.0 and 5.0.

$$D\_L(U) = \begin{cases} 1, & U < 10 \\ \frac{(20 - U)}{0.5}, & 10 \leq U \leq 20 \\ 0, & 20 \leq U \end{cases} \quad (5)$$

**Table 3.** Fuzzy rule base.

| Rule No. | RE | D | Classification |
|---|---|---|---|
| Rule_1 | L | L | LF_NN |
| Rule_2 | L | M | F_NN |
| Rule_3 | L | H | LF_NN |
| Rule_4 | M | L | MF_NN |
| Rule_5 | M | M | F_NN |
| Rule_6 | M | H | F_NN |
| Rule_7 | H | L | MF_NN |
| Rule_8 | H | M | MF_NN |
| Rule_9 | H | H | F_NN |

$$D\_M(U) = \begin{cases} 0, & U < 10 \\ \frac{(U - 10)}{0.5}, & 10 \leq U \leq 20 \\ 1, & 20 \leq U \leq 35 \\ \frac{(40 - U)}{0.5}, & 35 \leq U \leq 40 \\ 0, & 40 \leq U \end{cases} \quad (6)$$

$$D\_H(U) = \begin{cases} 0, & 35 < U \\ \frac{(U - 35)}{0.5}, & 35 \leq U \leq 40 \\ 1, & 40 \leq U \leq 50 \end{cases} \quad (7)$$

In a similar fashion, the fuzzification of the second input value of *D*, with different boundary conditions and same linguistic variables (Low, Moderate and High) are defined in Equation (5)–(7). Here, the lower limit is specified as 10 in (5), the middle bounds are set as 20 and 35 in (6) and (7) defines the upper limit as 40 and 50. To evaluate the input values in reference to the linguistic variables, rule base play a vital role which simply complies IF *X* AND *Y* THEN *Z* approach. Here, Mamdani model-based inference system is utilized and formatted in Table 3.

### 3.2. Defuzzification

The process of transforming evaluated fuzzy set into crisp output is known as defuzzification and is computed by various conventional proficiency methods like Mean of Maximum, the centroid of the area, weighted average, etc. Since our aim is to reduce computational cost, we opted to apply MoM [17] technique for defuzzification process. The fundamental principle aspects of fuzzy logic are referred from [18,19]. A simple and logical explanation for MoM [17] has been depicted diagrammatically in Figure 3, where $U_j$ denotes the control action of membership function which attains maximum and k represents the number of control action that taken part.

Thus, each $s_r$ acquires crisp output with multiple options to route the data packets. Inorder to route the packets, using fuzzy logic approach $s_r$ can distinguish its NN into three unique characteristics namely most favourable NN, favourable NN and least favourable NN. Figure 4 depicts fuzzy logic output variable which consists of three membership values that categorize the NN.
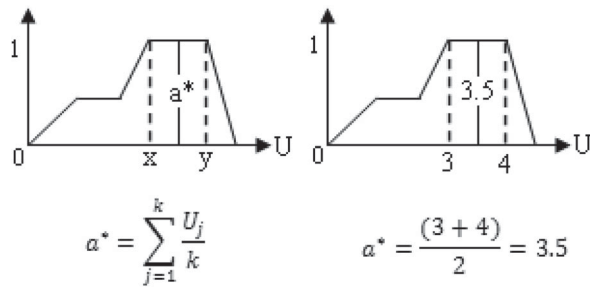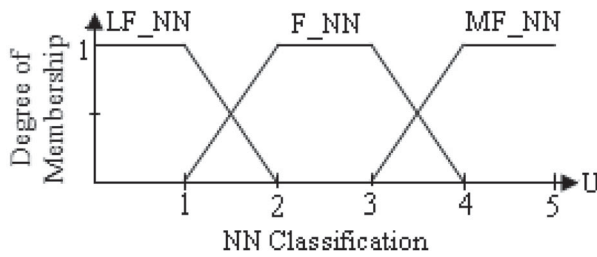
**Figure 3.** MoM defuzzification method.



**Figure 4.** Membership function *NN* classification.

(i) *MF_NN:* The first option of an electable neighbour node which poses high remaining energy level and optimal distance to *CN*
(ii) *F_NN:* Next to *MF_NN*, perhaps it is chosen to forward the packets when all *MF_NN* halts to operate due to permanent faults.
(iii) *LF_NN:* Last alternative to route the packets which pose very low energy level and non-optimal distance to *CN*.

## 4. Instant synchronization and fault-tolerant data routing

After the conclusion of defuzzification process, phase-IV commences for data transmission event, in which $s_r$ has multi-optional optimal *NN* to route the packets. Based on the fuzzy logic outcome each and every $s_r$ determines the *NN* to route the packets. As an initial step, the sender selects the NN and assigns a transmission timing slot. For allotting transmission slot, *TDMA* [20] technique is utilized. *TDMA* is a well-known channel access scheme which provides the capability to utilize maximum bandwidth without any collision. Once the *NN* receives the time slot and has the free channel to receive the packets, immediately sends its *TS* for synchronization with the sender. Then, the sender adjusts its clock according to the received *TS* and start sending its data packets.

Finally for each message transmission, the sender gets acknowledgement from the receiver. Due to the permanent fault at the receiver side, if the sender does not receive any acknowledgement in a particular period, then it decides to route the packets through another optional NN. Hence, sender's short waiting period to receive the acknowledgement is termed as
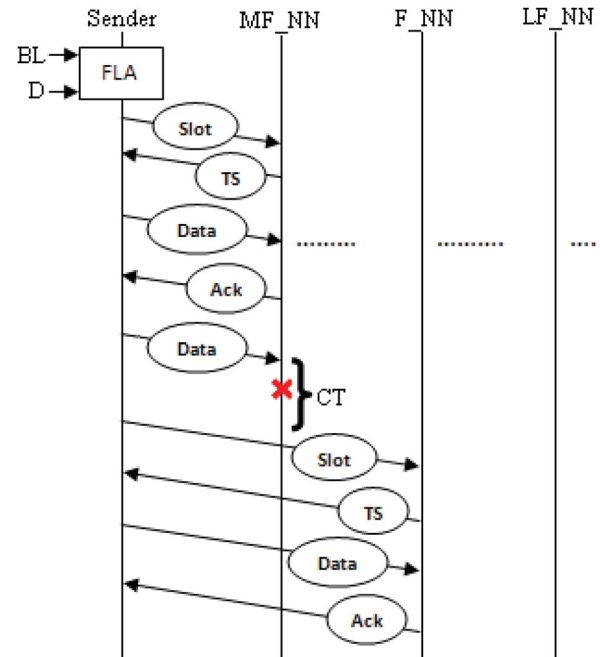


**Figure 5.** Data transmission and fault tolerance mechanism.

"critical time (*CT*)" Again sender performs the same slot assignment process with the newly preferred *NN*. On the completion of entire transmission between the sender and NN, again NN starts to forward the received packets towards *CN* by following the same slot assigning procedure. Thus, by tolerating the permanent fault, this mechanism ensures the effective end-to-end packet delivery with high probability. Figure 5 shows the diagrammatical description of the proposed work. Since most of the WSN-based RTS applications are the type of mission critical application, our proposed work is the right choice of adaptable form under various critical situations like collision, fire accidents, etc.

## 5. Simulation results and analysis

### 5.1. Implementation script

#### 5.1.1. System model
Our system model is presumed to comprise homogeneous sensor nodes regarding hardware units, and each one poses 5J as initial energy. All deployed nodes have the potentiality to execute FL standard processes. Here, the wireless communication among the nodes is of duplex type.

#### 5.1.2. Energy model
The conceptualization source of our energy model is ultimately cited from [15]. Thus, the formulated Equation (8) exhibits the energy consumption $(EC_t)$ of each $s_r$ per transmission in which $Elc_t$ denotes the energy consumption of transmission electronics. $A_{d1}$ and $A_{d2}$ represent the quantity of energy demanded the amp in free space and the multi-path model. Finally, *R*

and $MS_r$ represent the transmission range and transmitting message size of $r^{th}$ sensor node respectively.

$$EC_t = \begin{cases} (Elc_t + A_{d1}R^2)MS_r, & R < d_0 \\ (Elc_t + A_{d2}R^4)MS_r, & R \geq d_0 \end{cases} \quad (8)$$

Similarly, Equation (9) exhibits the receiver side energy consumption, where $Elc_r$ refers to the energy consumption of receiver electronics, and similarly, $MS_r$ represents receiving message size of the $r^{th}$ sensor node.

$$EC_r = (Elc_r MS_r). \quad (9)$$

### 5.1.3. Simulation specification

To analyse the entire nominated concept, the basic parametric configuration has to be concerned which in-turn used to examine the proposed novel facts. Thus, Mannasim framework of NS-2 simulator has been used for implementing and evaluating purpose. Few experimental parametric simulation values of interest are specified in Table 4.

### 5.1.4. Performance evaluation

In this evaluation section, we present the simulation results of the proposed mechanism. Though our approach is entirely focused on mission critical environments, the results are compared with some of the traditional and recent proactive as well as reactive routing protocols. For the betterment of our analysis, an advanced OLSR from [21], Fault tolerant DSR from [22] and AODV [23] routing protocols are considered. We evaluate the network consequences based on two aspects.

- Packet delivery ratio against the percentage of dead nodes.
- Total network energy consumption at each second throughout the simulation period.

**Table 4.** Simulation specifications.

| Type | Parameters | Values |
|------|-----------|--------|
| *Application* | Simulation Time, T | 20,000 s |
| | No. of milliseconds per slot | 40 s |
| | Events Generated | 1/slot |
| | Bandwidth | 1 Mbps |
| | Data Rate | 512 Kbps |
| | Beacon Data size | 10 bits |
| | Slot assignment Data size | 16 bits |
| | Critical Time (CT) | 10 s |
| *Network Topology* | Topology Size [ ] | 26.5 m × 2.4 m |
| | Network Type | Static |
| | No. of Nodes | 68 |
| | Channel | Wireless |
| *Radio Model* | Energy Model | Battery |
| | Initial Nodes Energy | 5.0 J |
| | Initial Nodes Transceiver Range | 50 metres |
| | Transmitter Electronics | 4.28 μJ/bit |
| | Receiver Electronics | 2.36 μJ/bit |
| | Transmit Amplifier | 100 pJ/bit/m² |
| | Listening/Idle | 2.36 μJ/bit |
| | Sleep Power | 0.00001 J/s |
| | Sensing Power | 0.000175 J/s |

The performance metrics of those two aspects are defined as

*Packet delivery ratio:* Ratio of the count of packets received by the destination node to the count of packets sent by the source node [22].

*Percentage of dead node:* The ratio of the number of dead sensor nodes due to the permanent fault to the number of fault-free sensor nodes in the network [24].

*Network Energy Consumption:* Energy consumed per event by $s_r$ node in receiving and sending data packets throughout the simulation period.

From the simulation result, it has been observed that at initial period, there is no major distinguishable difference in the performance of all the four protocols. Figure 6 shows that somehow the four protocols delivered the packets efficiently but when the percentage of dead nodes increases each of the protocol shows a significant difference among them. As compared, the performance of proposed work exhibits a positive evident in the delivery of packets at each event. When compared to the nominated work, the performances of others decline gradually as the percentage of dead node increases.

This performance execution is achieved because of adopting instant synchronization among routing nodes which not only forefend collisions but also ensures the availability of maximum bandwidth to each node. Thus, the proposed work guarantees the maximum range of delivering the critical packets in the prevalence of faults.

On the analysis of energy expenditure of entire network Figure 7 showcases the perfect optimal energy consumption of communicative node which is below 0.2 joules throughout the simulation. This result is possible because of the fuzzy logic outcome with less computational process. Moreover, the classification of *NN*
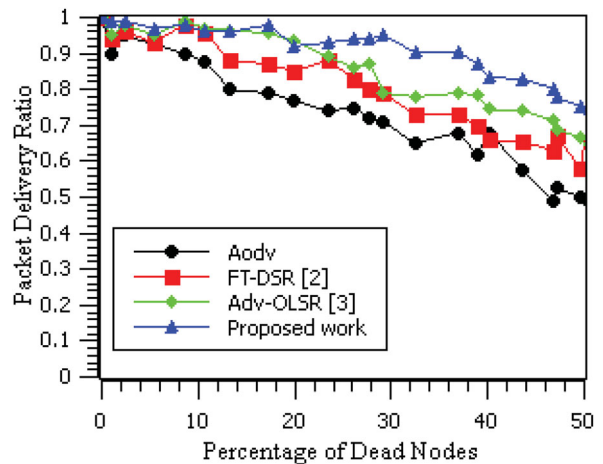


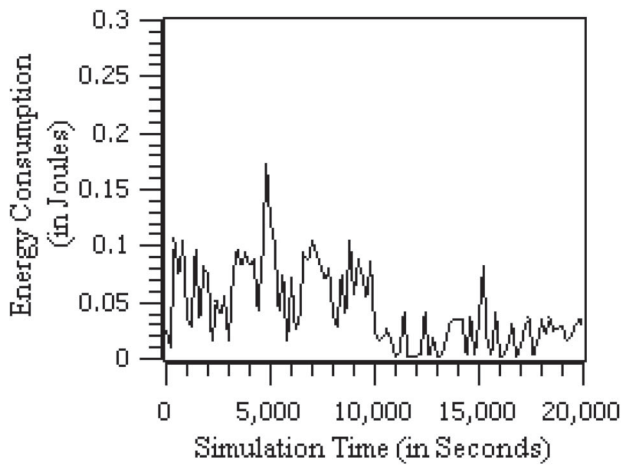**Figure 6.** Packet delivery ratio in the prevalence of permanent faults.

**Figure 7.** Energy consumption of entire network.

and packet routing through the selectable *NN* avoids unwanted routing overheads. The utilization of beacon signal plays a vital role in the management of optimal energy expenditure strategy because the size of the beacon signal is too small when compared to the data signal.

## 6. Conclusion

The outcome of the proposed work is consistent to manage any emergencies in RTS since it ensures the maximum packet delivery ratio. Adapting instant synchronization techniques reduce the collision and delay period during data transmission. Here, the undesirable and energy consuming process of allotting *TDMA* slots by a single controller or head node have been avoided, and each node has the choice to handle the procedure independently only when the events are generated. Most of the nodes have equal possibilities to get affected by potential faults like node failure due to battery depletion. Such nodes are notified during the fuzzy process and probably classified under *LF_NN*.

The short waiting juncture for acknowledgement known as critical time does not make any impact on end-to-end delay because it is fixed at 10 s which is only 25% of timing portion of entire slot time. Since the channel type is of wireless, there is the probability of data packet corruption. Our future work is expected to adapt packet lost recuperation scheme in our proposed method.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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