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Enhancing energy use efficiency of wireless sensor networks using newly proposed fault tolerance multipath routing protocol (MRP-FT)

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Abstract

The present study compared the newly proposed fault tolerance multipath routing protocol (MRP-FT) under the particle swarm optimization-based fault tolerant routing (PSO-FT) technique to the existing low-energy adaptive clustering hierarchy (LEACH) protocol applied in different combinations of inter-node numbers (N) ranging from 100 to 300 nodes $(N_{100-300})$ in wireless sensor networks (WSNs) with different area sizes $(X_m \times Y_m)$ of 100–1000 m^2 $(WSN_{100-1000})$ to enhance energy efficiency and reliability of WSNs. The implementation of MRP-FT protocol significantly decreased the packet overhead by 36.0–69.5%, delay by 40.4–52.9%, and energy consumption by 35.9–52.9%, while increasing reliability by 97.0–104.1%, compared to the existing LEACH protocol. For instance, at $N_{100-200}$, the LEACH simulated packet overhead increased from 76-89 packets at t = 500 s with an increase in WSN size from 100 to 1000. At $N_{300} + WSN_{100}$, the packet overhead showed the highest decrease of ca. 69.5% with MRP-FT over the LEACH protocol. The implementation of the MRP-FT protocol reduced energy consumption by 35–123 J over the LEACH protocol.

Keywords: *LEACH protocol, MRP-FT protocol, energy consumption, time delay, packet overhead, reliability*

1. Introduction

Wireless sensor networks (WSNs) are composed of a vast number of tiny, low-cost, self-configured, and multi-functional sensor nodes [8, 15, 25]. These are designed to operate in severe and remote environments, and their deployment is often done in an ad-hoc and self-organized manner which make them exceptionally appropriate for applications, where wired networks are not feasible and/or cost-effective [2, 29]. These nodes typically consist of an analog-to-digital converter, micro-controller, memory, radio electronics, antenna, and the battery [7, 28, 29, 51]. The sensor nodes are embedded systems that work collectively to monitor an environment and/or a system [6, 15, 43, 45]. They are randomly deployed in physical

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environments to sense, collect, aggregate, and transmit data among themselves and/or to the base stations (BSs) [3, 29, 36, 48, 49], which enables communication feasible in short distances without any physical tethering [4]. However, these sensor nodes are battery powered [2, 37, 39], which makes networking systems highly challengeable because the replacement and/or recharge of batteries is not feasible, particularly in the hostile and remote locations [6, 7, 17]. Therefore, it is essential to consider the longevity of the battery energy drain for the sensor nodes to perform efficiently, when designing a routing channel within the network [2]. The communication sub-systems are known to consume a significant amount of energy, which ultimately determines the lifespan of WSNs [16, 43, 45, 49, 77, 80].

The constraint of energy consumption in the deployment of a large number of sensors has made routing in WSNs a significant challenge [23, 80]. To extend the lifespan of sensor nodes and to maximize energy efficiency by minimizing the energy consumption in sensing, it is important to design energy-efficient protocols [3, 6, 33, 45]. The development of energy-efficient protocols is considered crucial to extend and maximize the energy use efficiency and lifespan of sensor nodes [64, 68, 70, 76]. The uniform distribution of routing protocols is considered a pre-requisite for ensuring the better working of WSNs on a large scale [10, 39, 43]. However, to ensure effective communication, the cluster heads (CHs) should be evenly distributed in the network area, enabling sensor nodes to find CHs equally [15, 72]. Additionally, the communication between CHs and BSs needs to be minimized because the maximum energy is consumed during communication between CHs and BSs [2, 18, 79]. Therefore, the selection of appropriate protocols capable of helping sensor nodes to transfer data successfully and energy efficiently is critically important [64, 76]. One such protocol is a routing protocol that involves routing of information from one node to another and from nodes to BSs by following some specific rules [23]. Among the existing routing protocols, such as data-centric routing, hierarchical routing, source-initiated routing, destination-initiated routing, and the location-based routing protocols are widely applied [25, 26, 38, 39, 44, 50, 71].

In hierarchical routing protocols, WSNs are divided in a number of clusters, and for each cluster, there is only one node which communicates with the BSs [5, 14, 20, 26]. The hierarchical protocols use data aggregation and fusion to reduce the number of transmitted messages to the BSs [26, 39, 50], and while doing so, all sensor nodes has a chance to become a CH [1, 5, 38, 39]. Amongst the hierarchical routing protocols, low energy adaptive clustering hierarchy (LEACH) has been the most widely used protocol for dynamic clustering in WSNs [14, 33, 35, 42]. In most of the hierarchical routing protocols including LEACH, CHs selection technique is not highly energy efficient [29, 33, 59, 68]. Therefore, to enhance energy efficiency, fault tolerance is considered to play a key role in enhancing lifespan of WSNs [4, 19–21, 47]. To improve fault tolerance, the multipath routing mechanism has usually been implemented to replace the original single path routing mechanism [44, 53, 66]. The multipath routing protocol has abilities of transferring packets through two or more paths, while reducing the packet loss rate [50, 61, 63]. Notwithstanding these advantages, the multipath routing protocols help reducing packet tampering and/or malicious attacks in the routing process to recover the security of data transmission [11, 12, 65]. Hierarchical routing protocols are commonly used in WSNs to reduce the number of transmitted messages to the BSs and to improve energy efficiency and fault tolerance [4, 19]. In these protocols, the network is divided into a number of clusters, and each cluster has only one node that communicates with the BSs [5, 26]. Data aggregation and fusion techniques are used to further reduce the number of messages transmitted to the BSs [14, 26], and all sensor nodes have a chance to become a CH

[1, 5]. Among hierarchical routing protocols, the LEACH has been widely used for dynamic clustering in WSNs [33, 35, 36, 42]. However, the CH selection technique in most hierarchical routing protocols, including LEACH, is not energy efficient [29, 33, 59, 68]. To improve fault tolerance, multipath routing mechanisms have been implemented to replace the original single path routing mechanism [53, 66]. Multipath routing protocols have the ability to transfer packets through two or more paths, thereby reducing the packet loss rate [61, 63]. In addition to these advantages, multipath routing protocols can also reduce packet tampering and/or malicious attacks in the routing process, thereby improving the security of data transmission [11, 65]. To summarize, hierarchical routing protocols and multipath routing mechanisms have become popular techniques to improve energy efficiency, fault tolerance, and security in WSNs. However, the CH selection technique in most hierarchical routing protocols needs to be further improved to enhance the energy efficiency of the network. Meanwhile, multipath routing protocols can provide a reliable solution to reduce packet loss and improve security in WSNs.

Recently, Kaur [46] reported the superiority of the fault tolerance multipath routing (MRP-FT) protocol over the existing LEACH protocol, based upon a substantial energy saving of 15 J (ca. 38.5%) coupled with a reduced delay of 22 packets, compared to the existing PSO-FT technique-based LEACH protocol. The multipath routing algorithm establishes multiple paths between the source and destination node, which offers a certain selection probability based on energy consumption, time delay, and bandwidth of the network link, and data are transmitted through multiple paths for increased link performance [37, 66]. The fault-tolerant routing protocol has high error recovery and error detection abilities [19], with a three-dimensional space and regional coevolution. These protocols, with the ability to take into consideration the residual energy of nodes and the deviation angle, help reduce time delay while enhancing energy consumption in the multipath structure in WSNs [56]. The earlier research comparing the applicability of LEACH and MRP-FT protocol had a limitation of being focused on a narrow range of the number of internodes (N_{100}) in smaller area sizes of WSNs (WSN_{100}) [46]. Nowadays, WSNs include a tremendous number of nodes that are deployed in several areas. Therefore, comparisons at high resolution, such as $N_{300} + WSN_{1000}$, would help determine the scalability of the protocols. To summarize, given the lack of information regarding a high-scale comparison of protocols (LEACH vs. MRP-FT), the present study was conducted to compare various combinations of the number of inter-nodes from 100 to 300 nodes $(N_{100}\text{–}N_{300})$ in different area sizes $(X_m \times Y_m)$ of WSNs ranging from 100×100 m^2 to 1000×1000 m^2 $(WSN_{100-1000})$ for enhancing energy use efficiency and reliability, while decreasing time delay in WSNs. The present study would help decide the scalability of WSNs, while making them more energy-efficient.

2. Methodology

2.1. Low energy adaptive clustering hierarchy (LEACH) protocol

The LEACH protocol is designed to randomly select sensor nodes from a network of CHs based on their euclidean distance, while the remaining nodes act as cluster member nodes [62]. The resulting cluster member nodes gather data and broadcast it to the CHs, which then communicate with the BSs through single-hop communication [35, 36]. The LEACH protocol divides the WSNs into clusters of equal sizes with balanced weightage among all the nodes [52], and the CHs rotate periodically, with each round divided into two stages, viz. the establishment phase and the stable transmission phase.

The establishment phase ensures CH selection through a specific CH selection process, while the stable transmission phase transfers gathered information from the nodes to the CHs and aggregated data from the CHs to the sink node [40]. The LEACH maintains hierarchy by upholding the sink, CHs, and cluster nodes, with the sink being the central BS that receives gathered information from all the nodes [22, 74]. After receiving the information, the CHs collect and transmit the gathered information to the sink node [38, 39]. Despite its balanced weightage approach, a major disadvantage of the LEACH protocol is that the limited capacity of CHs can overload them, preventing them from receiving and transmitting gathered data to the sink node [9, 52]. Additionally, if CHs are far away from the sink node, they may dissipate energy and eventually lose much of it, resulting in inefficient energy management and reduced lifespan [67, 78]. Random CH selection can also lead to inefficient energy management if a CH dies, resulting in the loss of gathered information [13, 35]. To address these issues, the present study proposes selecting CHs based on the energy level of the sensor node and the weightage assigned to them. The selected CHs along the euclidean distance must satisfy the assigned energy weightage [67]. Overall, the LEACH protocol's hierarchical structure and balanced weightage approach have advantages, but its limited CH capacity and potential for inefficient energy management highlight the need for improved protocols.

The energy required for the CHs is given by the following equations:

$$E_{CH} = nk(E_{\text{elec}} + E_{fs}d^2) \text{ for } d < 0 \tag{1}$$

$$E_{CH} = nk(E_{\text{elec}} + E_{\text{amp}}d^4) \text{ for } d \geq 0 \tag{2}$$

where E_{CH} is energy required by the CH, n – number of nodes assigned for the cluster, k – number of message bits, E_{elec} – energy required for transmitting and receiving the data bit, E_{fs} and E_{amp} – parameters for calculating the E-bit message transmitting over free space multi-path propagation and d – transmitting distance towards the sink node. Equation (2) represents the CH election using the k-means algorithm.

$$f = \sum_{c=1}^{m} \sum_{y \in g_c}^{m} (y_i - h_c)^2 \tag{3}$$

where F is the function of the k-means algorithm, c – number of clusters, y – mote of the cluster, and h – head to be elected. The Euclidean distance is estimated using equation

$$d(y_i, h_c) = (y_i - h_c)^2 \tag{4}$$

2.2. Fault tolerance multipath routing protocol (MRP-FT)

A new routing protocol is proposed that is highly energy-efficient in larger network areas of WSNs. In this protocol, the collected information is highly interconnected and the requirements of the end-users are high-level functions that collect events from the environment. In the MRP-FT clustering hierarchical protocol, optimized routing algorithms are essential for designing efficient solutions for larger scale WSNs [32, 69]. The homogeneous sensor nodes are randomly positioned in the network area, and the forwarder node is located in an area where it is highly involved in the communication process. In the set-up phase, the network area is divided into three logical stages, namely S1, S2, and S3, based on the positioning of sensor nodes in the network field, and the BSs are responsible for dividing the network field into these three logical stages. The S1 and S3 have clustered regions, while S2 is a non-clustered region. The sensor nodes in S1 transmit information to the CHs, and the aggregation is achieved by the CHs. The gathered information is then sent to the BSs. The sensor nodes in S2 transmit gathered information to the forwarder node, which performs aggregation on the gathered data, and then the aggregated data is forwarded to the BSs. The sensor nodes belonging to S3 transmit gathered data to the CHs, and aggregation begins, after which the CHs transmit information to the forwarder node. However, some portions of the WSN may get more CHs, while other portions may get fewer, which can cause that portion of the network area to expire earlier [8].

In MRP-FT, the BSs divide the network area into multiple logical segments and evenly distribute the CHs in each segment of the network field. Such a cluster formation strategy helps to increase the overall lifespan of the WSNs. Based on location information, segment identification numbers are allocated to sensor nodes. As a result, sensor nodes can only join CHs located in their own segment [69]. Immediately after cluster formation, each node decides whether or not to serve as a CH for the existing round. In the process, each sensor node elects itself as a CH based on the desired ratio of CHs and the status of eligibility flag to become a CH. For example, sensor node n selects a random number ranging from 0 to 1. The node will become a CH if the threshold $T(n)$ is greater than a number calculated using equation [36, 59, 80].

$$T(n) = \begin{cases} \dfrac{P}{1 - P\left(r\left(\dfrac{1}{P}\right) - \left\lfloor r\left(\dfrac{1}{P}\right)\right\rfloor\right)}, & \text{if } n \in G \\ 5, & \text{otherwise} \end{cases} \tag{5}$$

where n is the total number of sensor nodes, P – preferred the percentage of CH, r – current round, G – set of sensor nodes eligible to become CH, P – the percentage of CH in all nodes, r – the number of current election rounds, $r\lfloor(1/P)\rfloor$ – the number of nodes that have been selected in this round and G – the set of nodes without CHs selected in this round.

2.3. Performance evaluation of existing and proposed protocols

The simulations were conducted using MATLAB R2013b, which provided an interactive environment for algorithm deployment, data visualization, and numeric computation. The homogeneous sensor nodes were randomly deployed to simulate the existing LEACH and proposed MRP-FT routing protocols.

2.4. Parameters selection used for simulations

The initial simulation parameters for evaluating the existing LEACH and proposed MRP-FT protocols were implemented on WSNs with variable network sizes ranging from 100 m to 1000 m (Table 1). Earlier research by Kaur [46] demonstrated the superiority of the MRP-FT protocol over LEACH in enhancing energy efficiency and reliability, which forms the basis of this study. To address the increasing demand for enhancing energy efficiency in large network area sizes, different scenarios were integrated with increased numbers of nodes $(N_{100-300})$and WSN sizes $(WSN_{100-1000})$ in various combinations to determine the scalability of the newly proposed protocol. The probability of selecting CHs was kept uniform

($p = 0.1$), and the transmission energy (E_{TX} $(d < d_0)$) and receiving energy E_{RX} of nodes were set to 50 nJ·bit^{-1}, based on earlier research [41]. The energy dissipated in free space $(\in fs)$ was kept equal to 10 pJ·bit^{-1}·m^{-1}. The data aggregation energy E_{DA} of 5 nJ·bit^{-1} message was considered for each scenario studied. A uniform packet size of 1000 bits was used, and the threshold values $(\alpha, \beta$, and $\gamma)$ were set to 0.3333. The maximum number of rounds $R_{\max}$ was uniformly set to 200 for each scenario studied (Table 1). For each network size, 100 random network topologies were generated to estimate the average number of discovered paths using 200 iterations.

Table 1. Detailed description of simulation parameters considered in the execution of MRP-FT and the existing LEACH protocol for wireless sensor networks (WSNs)

Parameter	Description	Acronyms and their values	
		LEACH protocol	MRP-FT protocol
$X_m \times Y_m$	network area size (04; 100–1000 m) in different combinations WSN_{100}, WSN_{250}, WSN_{500} and WSN_{1000}	WSN_{100}	WSN_{100}, WSN_{250}, WSN_{500} and WSN_{1000}
N	number of nodes (03; 100-300 nodes) in different combinations: N_{100}, N_{200} and N_{300})	N_{100}	N_{100}, N_{200} and N_{300}
$R_{\max}$	number of rounds	200	
P	probability selected as cluster heads (CHs)	0.1	
E_0	initial energy of the node	0.5 J	
E_{TX} $(d < d_0)$	transmission energy of a node	50 nJ· bit^{-1}	
E_{RX}	receiving energy of node	50 nJ· bit^{-1}	
E_{DA}	data aggregation energy	5 nJ nJ· bit^{-1} message	
ϵ_{fs}	energy dissipation on free space	10 pJ·bit^{-1}· m^{-2}	
ϵ_{mp}	energy dissipation of multi-path delay	0.0013 pJ· bit^{-1}· m^{-4}	
Packet	packet size	1000 bits	
α, β, γ	threshold values	0.3333	

3. Results

3.1. Performance evaluation of $N_{100-300} + WSN_{100}$ networks

Figure 1 displays the comparison of WSNs' performance between the LEACH and MPR-FT protocols at $N_{100} + WSN_{100}$. The relationship between the number of dead nodes and the time of operation showed a significant difference in terms of energy consumption, reliability, delay, and packet overhead between the two protocols. The packet overhead remained relatively constant up to 2750 s with the implementation of MPR-FT, while it was constant up to 3050 s with the LEACH protocol. These findings indicated that the packet overhead at t = 5000 s was reduced by ca. 34.6 bytes (ca. 46.0%) with MRP-FT, compared to the LEACH protocol. The energy consumption increased from 0–100 J during t = 2200-5000s with MPR-FT at $N_{100} + WSN_{100}$, while it only increased from 0–45 J during 2500-5000 s with the implementation of LEACH protocol. The comparison revealed that MRP-FT had higher energy efficiency of 52 J at t = 5000 s as compared to LEACH at $N_{100} + WSN_{100}$. The delay in packet overhead transfer was reduced to 46 s with MRP-FT, compared to 81 s for LEACH at $N_{100} + WSN_{100}$, and a decrease of ca. 43.2%. Similar to other variables, reliability was higher (200%) for MRP-FT as compared to LEACH at t = 5000 s (Table 2).

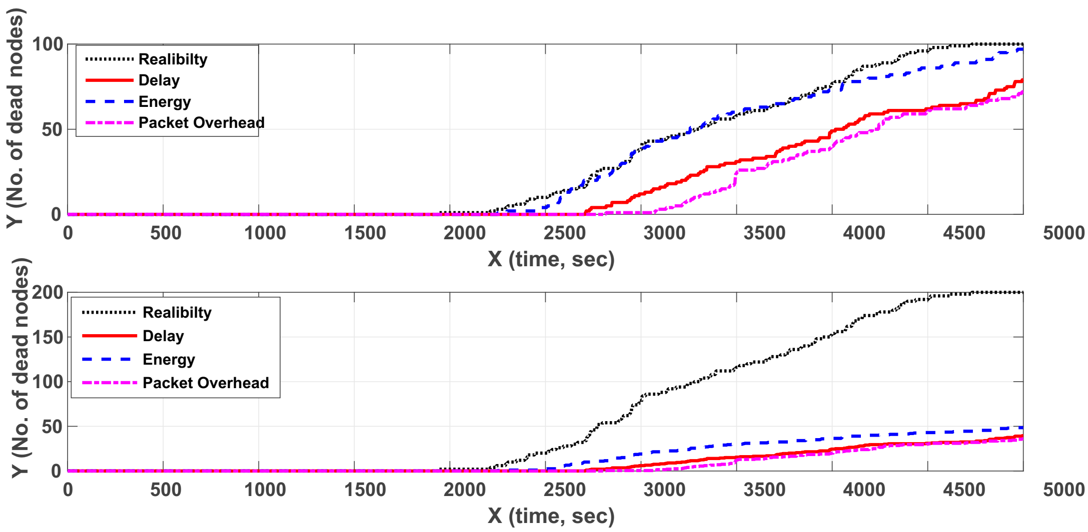

Figure 1. Reliability (in %), delay (in sec), energy consumption (in J) and packet overhead (in bytes) compared with existing LEACH vs. newly proposed MRP-FT protocol executed with $N_{100} + WSN_{100}$

Table 2. Packet overhead, delay, energy, and reliability achieved with the implementation of existing LEACH protocol vs. MRP-FT executed in different combinations of number of nodes and area size of and area size of 100×100 m^2

Protocol	Packet overhead	Delay (packets)	Energy [J]	Reliability [%] (at 5000 s)
LEACH (N_{100}, WSN_{100})	76	81	100	100
MRP-FT (N_{100}, WSN_{100})	44	46	48	200
LEACH (N_{200}, WSN_{100})	155	172	196	200
MRP-FT (N_{200}, WSN_{100})	73	81	92	400
LEACH (N_{300}, WSN_{100})	246	273	267	300
MRP-FT (N_{300}, WSN_{100})	75	150	152	600

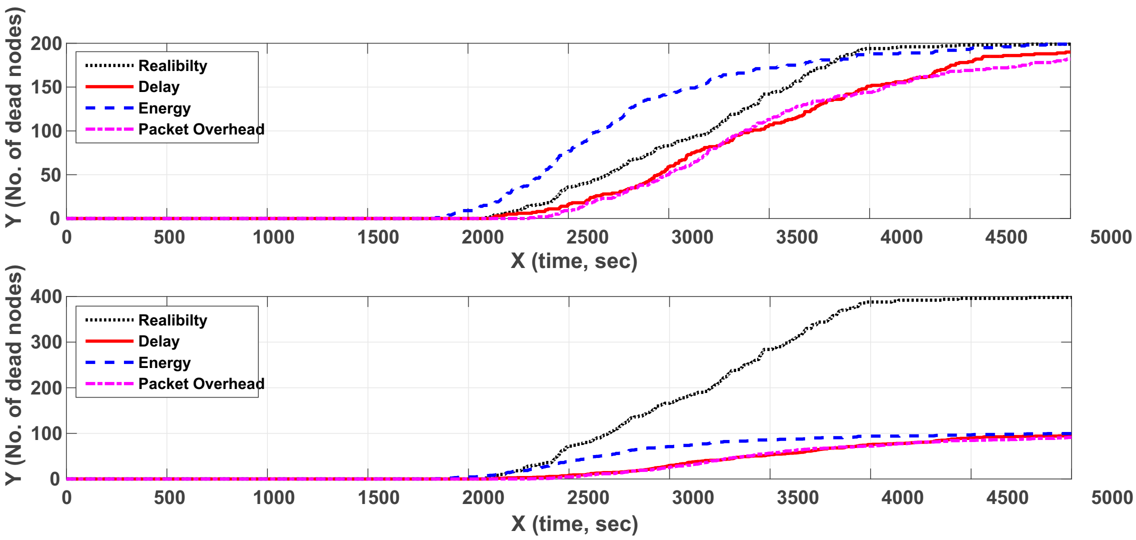

Figure 2. Comparison of reliability (in %), delay (in sec), energy consumption (in J) and packet overhead (in bytes) with existing LEACH vs. newly proposed MRP-FT protocol executed with $N_{200} + WSN_{100}$

The implementation of these protocols at $N_{200} + WSN_{100}$ resulted in a similar response in terms of reliability, delay, packet overhead, and energy consumption as a function of time (Figure 2). At $N_{200} + WSN_{100}$, the packet overhead was reduced from 155 to 73 bytes (by ca. 52.9%) at t = 5000 s with the implementation of MRP-FT over the LEACH protocol (Table 2). The energy consumption of 196 J for LEACH, compared to 92 J for MRP-FT at $N_{200} + WSN_{100}$, was achieved at t = 5000 s. These results revealed an energy consumption saving of 104 J (by ca. 53.1% with the implementation of MRP-FT over the existing LEACH protocol. The reliability was increased to 400% at t = 5000 s for MRP-FT over LEACH (200%) at $N_{200} + WSN_{100}$. Figure 3 shows the relationship between the number of dead nodes and time. These findings indicated a decreased packet overhead by 171 bytes (by ca. 69.5%) for MRP-FT over LEACH at $N_{300} + WSN_{100}$ (Table 3). A delay in packet transfer of 273 packets for LEACH and 150 for MRP-FT at $N_{300} + WSN_{100}$ revealed a decreased delay by ca. 45.1%.

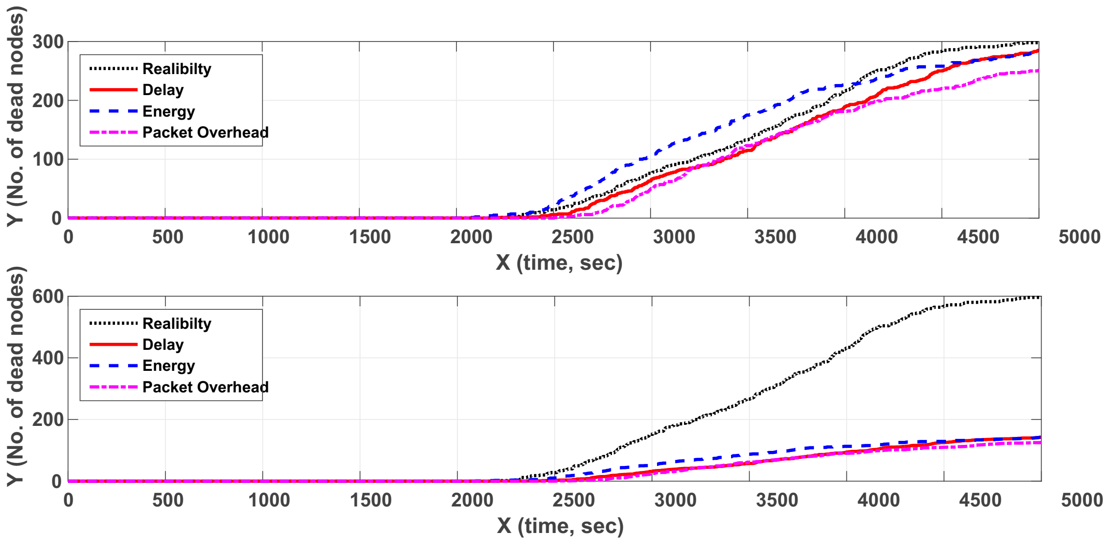

Figure 3. Comparison of reliability (in %), delay (in sec), energy consumption (in J) and packet overhead (in bytes) with existing LEACH vs. newly proposed MRP-FT protocol executed with $N_{300} + WSN_{100}$

Table 3. Packet overhead, delay, energy and reliability achieved at 5000 s with the implementation of existing LEACH protocol vs. newly proposed MRP-FT executed in different combinations of number of nodes and area size of 250×250 m^2 of WSNs

Protocol	Packet overhead	Delay (packets)	Energy [J]	Reliability [%]
LEACH (N_{100}, WSN_{250})	93	94	100	100
MRP-FT (N_{100}, WSN_{250})	49	48	200	200
LEACH (N_{200}, WSN_{250})	198	197	150	200
MRP-FT (N_{200}, WSN_{250})	98	99	300	400
LEACH (N_{300}, WSN_{250})	295	294	175	300
MRP-FT (N_{300}, WSN_{250})	173	172	300	600

The research conducted in this study suggests that MRP-FT is a better protocol for enhancing energy efficiency, reliability, delay, and packet overhead compared to the LEACH protocol. Additionally, the scalability of the MRP-FT protocol was demonstrated by integrating different scenarios with increased numbers of nodes and the size of WSNs, thus highlighting its applicability to a larger networks. The uniform packet size of 1000 bits, threshold values (α, β, and γ) of 0.3333, maximum number of rounds $R_{\max}$ of 200, and other parameters used in this study were based on earlier research and chosen appropriately for each scenario studied (Table 1).

3.2. Performance evaluation of $N_{100-300} + WSN_{250}$ networks

Based on the experimental results shown in Figures 4–6, there was a significant improvement in the reliability, delay, packet overhead, and energy consumption of WSNs with the implementation of LEACH and MRP-FT protocols at $N_{100-300} + WSN_{250}$ at t = 500 s. Initially, the packet overhead remained relatively constant up to t = 550 s for LEACH and up to 850 s for MRP-FT protocol at $N_{100-300} + WSN_{250}$.

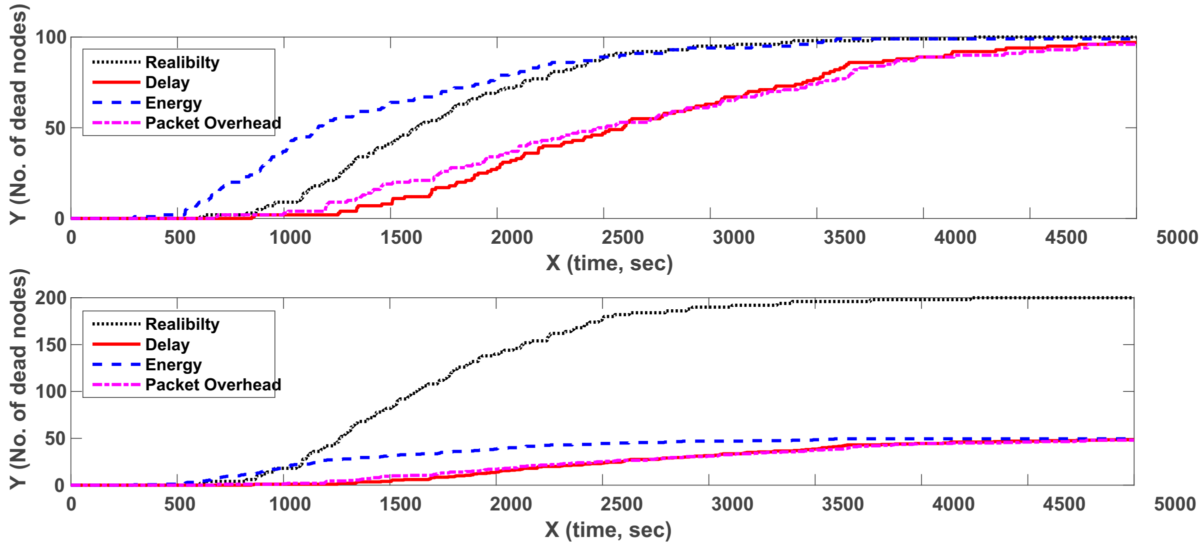

Figure 4. Comparison of reliability (in %), delay (in sec), energy consumption (in J) and packet overhead (in bytes) with existing LEACH vs. newly proposed MRP-FT protocol executed with $N_{100} + WSN_{250}$

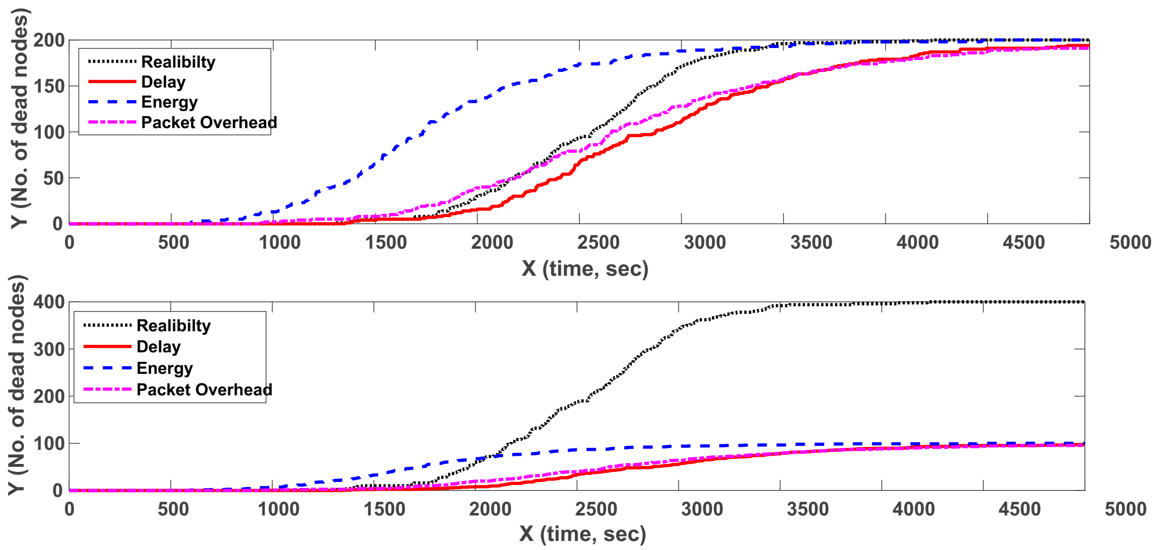

Figure 5. Comparison of reliability (in %), delay (in sec), energy consumption (in J) and packet overhead (in bytes) with existing LEACH vs. newly proposed MRP-FT protocol executed with $N_{200} + WSN_{250}$

Afterward, there was a sharp increase in packet overhead up to 3500 s for LEACH protocol, followed by a gradual increase. In contrast, for MRP-FT protocol implemented at $N_{100-300} + WSN_{250}$, although there was a sharp increase for the same period, the packet overhead decreased by 44 packets (ca. 47.3%) at t = 5000 s. Energy consumption increased sharply at t = 350 s and reached its maximum at t = 1490 s, but it was two times higher for MRP-FT as compared to 100% for LEACH at $N_{100-300} + WSN_{250}$. The delay in packet overhead of 94 and 48 packets, respectively for LEACH and MRP-FT, indicates a decrease of ca. 48.9% over LEACH.

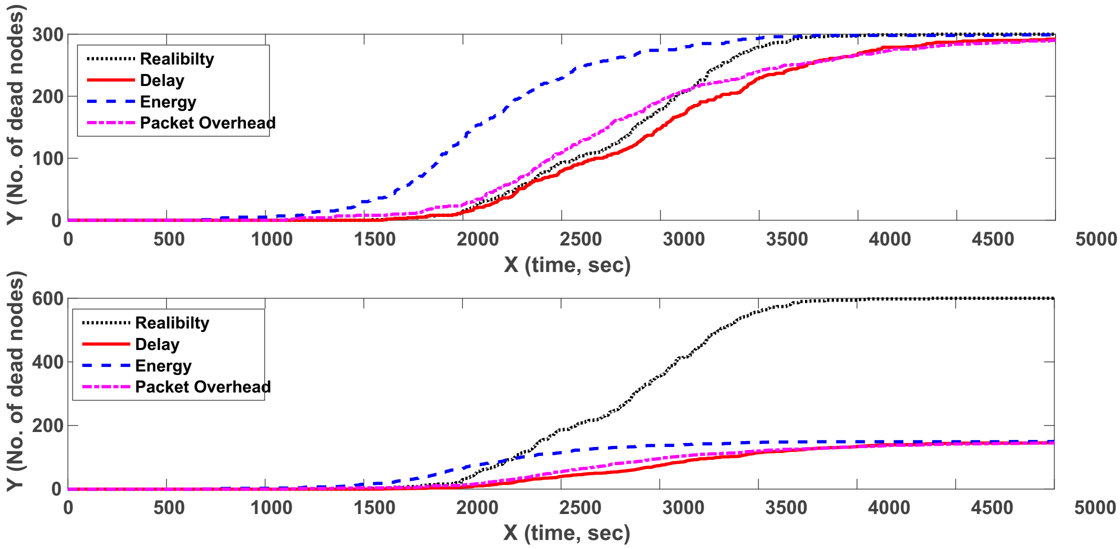

Figure 6. Comparison of reliability (in %), delay (in sec), energy consumption (in J) and packet overhead (in bytes) with existing LEACH vs. newly proposed MRP-FT protocol xecuted with $N_{300} + WSN_{250}$

At $N_{200} + WSN_{250}$, packet overhead remained constant initially up to t = 930 s for LEACH and t = 1490 s for MRP-FT protocol. There was a gradual increase in packet overhead up to t = 2000 s, followed by a sharp increase thereafter, which leveled-off at t = 3900 s. At t = 5000 s, packet overhead of 198 for LEACH and 98 for MRP-FT was observed, indicating a decreased packet overhead by ca. 50.5% with the implementation of MRP-FT protocol. A delay of 98 packets was observed at t = 5000 s for MRP-FT over LEACH implemented at $N_{200} + WSN_{250}$. The energy consumption increased by 150 J with increased reliability of 200% with the implementation of MRP-FT over LEACH protocol. At $N_{300} + WSN_{250}$, packet overhead remained relatively constant up to t = 1430 s for LEACH, while up to t = 1775 s for MRP-FT. At the longest time interval (t = 5000 s), packet overhead of 295 and 173 packets for LEACH and MRP-FT protocols was observed. These results revealed a decreased packet overhead of 122 packets ca. 41.4%) with the implementation of MRP-FT protocol. The decreased packet overhead was manifested with a decreased delay of ca. 41.5% for MRP-FT protocol at $N_{300} + WSN_{250}$. There was an increase in energy consumption by 125 J (ca. 71.4%) and reliability from 300 to 600% with the implementation of MRP-FT over LEACH protocol.

3.3. Performance evaluation of $N_{100-300} + WSN_{500}$ networks

The implementation of both existing and proposed protocols in larger WSNs with a larger number of nodes resulted in significant changes in the response curves for packet overhead, energy consumption, delay, and reliability (Figures 7–9). The results showed that both protocols achieved similar reliability with lower energy consumption and packet overhead transfer in almost half the time period. Figure 7 illustrates a sharp and sudden increase in packet overhead, energy consumption, and delay simulated with LEACH protocol at $N_{100} + WSN_{500}$ during the initial time period, reaching a maximum at t = 2500 s, followed by a gradual increase thereafter.

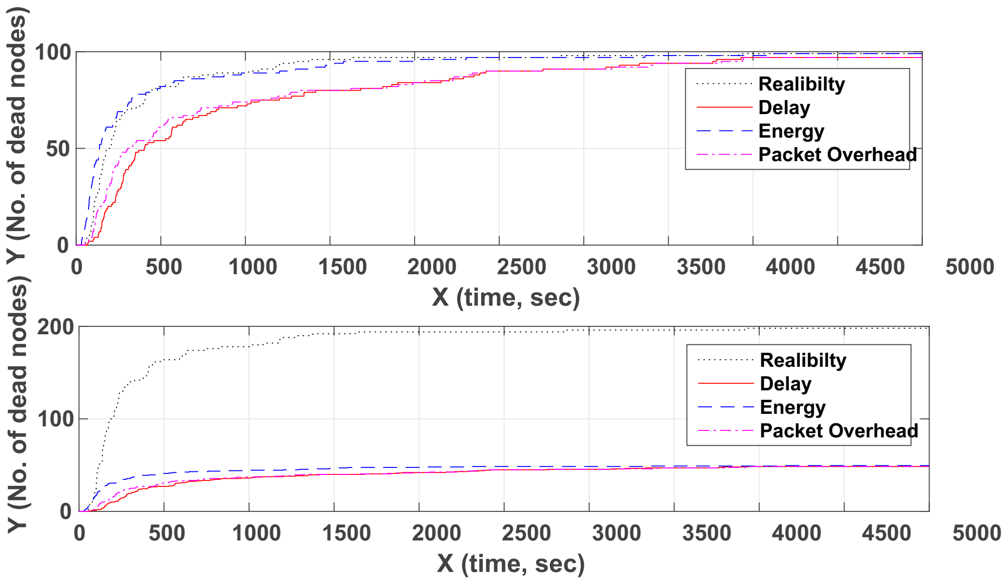

Figure 7. Comparison of reliability (in %), delay (in sec), energy consumption (in J) and packet overhead (in bytes) with existing LEACH vs. newly proposed MRP-FT protocol executed with $N_{100} + WSN_{500}$

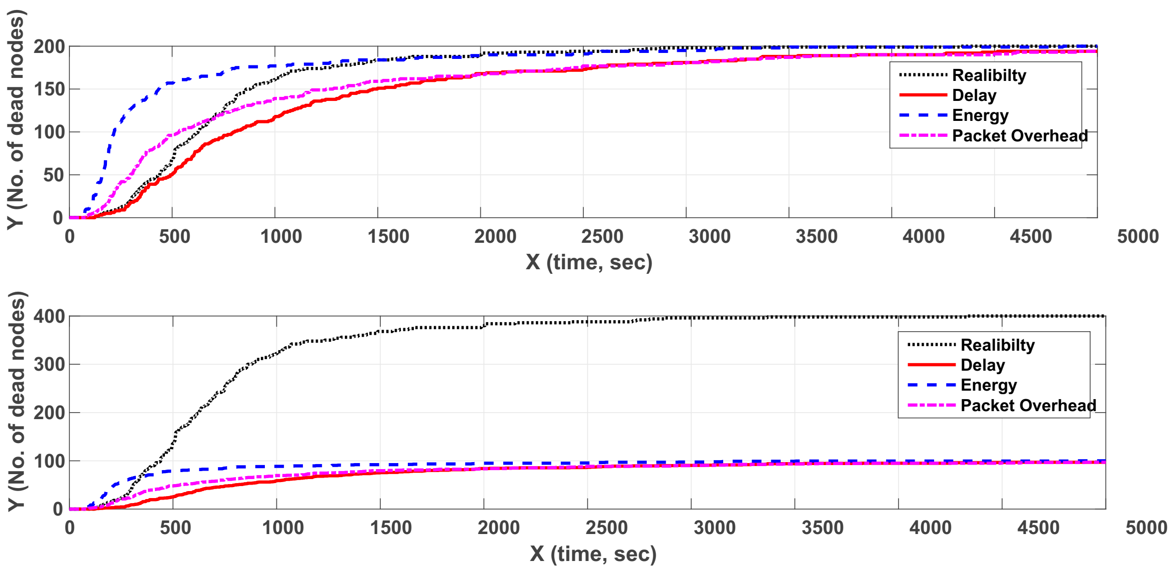

Figure 8. Comparison of reliability (in %), delay (in sec), energy consumption (in J) and packet overhead (in bytes) with existing LEACH vs. newly proposed MRP-FT protocol executed with $N_{200} + WSN_{500}$

The implementation of MRP-FT protocol resulted in a sharp increase in reliability and reached its maximum at t = 2500 s. At $N_{100} + WSN_{500}$, the packet overhead was decreased by 43 packets even at 2500 s (by ca. 52.3%) with the implementation of MRP-FT over the existing LEACH protocol. Additionally, a decreased energy consumption of 47 J (by ca. 48.6%) coupled with increased reliability of ca. 97% was achieved at t = 2500 s. Figure 8 illustrates the response of WSN variables simulated using both protocols at $N_{200} + WSN_{500}$, which resulted in an increase in packet overhead due to the increased number of nodes N_{100} to N_{200} at WSN_{500}. The packet overhead decreased from 176 to 98 packets (a decrease of ca. 44.3%) with the implementation of MRP-FT over the LEACH protocol at $N_{200} + WSN_{500}$. The energy consumption decreased by 97 J (by ca. 49.5%) for MRP-FT over the LEACH protocol. The implementation of MRP-FT protocol at $N_{200} + WSN_{500}$ resulted in an increased reliability from 196 to 395% (Table 4).

Table 4. Packet overhead, delay, energy and reliability at 2500 s achieved with the implementation of existing LEACH protocol vs. newly proposed MRP-FT executed in different combinations of number of nodes and area size of 500×500 m^2 of WSNs

Protocol	Packet overhead	Delay (packets)	Energy [J]	Reliability [%]
LEACH (N_{100}, WSN_{500})	92	93	97	100
MRP-FT (N_{100}, WSN_{500})	49	49	50	197
LEACH (N_{200}, WSN_{500})	176	175	196	196
MRP-FT (N_{200}, WSN_{500})	98	97	99	395
LEACH (N_{300}, WSN_{500})	267	268	292	293
MRP-FT (N_{300}, WSN_{500})	169	165	174	589

The response of different simulation variables in relation to the time period of implementation of both protocols at $N_{300} + WSN_{500}$ is shown in Figure 9. These results revealed that packet overhead decreased by ca. 36.7% at t = 2500 s for MRP-FT, compared with the LEACH protocol. The decreased energy consumption by 118 J (by ca. 58.9%) was achieved with increased reliability of ca. 101% with MRP-FT over the LEACH protocol implemented at $N_{300} + WSN_{500}$.

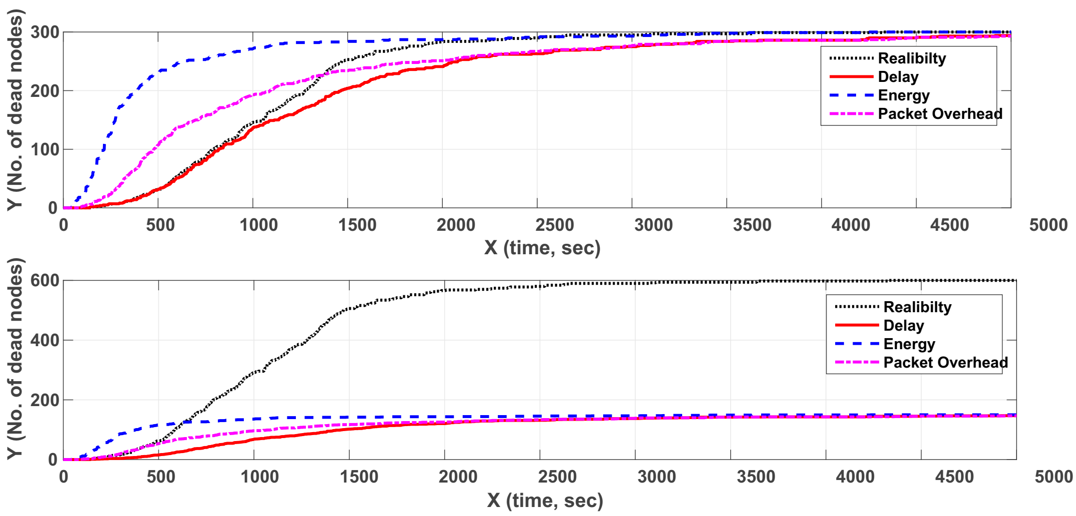

Figure 9. Comparison of reliability (in %), delay (in sec), energy consumption (in J) and packet overhead (in bytes) with existing LEACH vs. newly proposed MRP-FT protocol executed with $N_{300} + WSN_{500}$

3.4. Performance evaluation of $N_{100-300} + WSN_{1000}$ networks

A drastic change in response curve was observed for $N_{100-300} + WSN_{1000}$ as compared to the lower WSN area range (Figures 10–12). Figure 10 showed that the packet overhead, delay, reliability, and energy consumption attained their maxima during the initial time period $(t = 50s)$ for LEACH protocol, followed by a no-change phase with the passage of time. The implementation of MRP-FT over existing LEACH protocol decreased the packet overhead by ca. 44.9%. This decrease was achieved with saving of energy use of 46 J (ca. 48.9%) and increased reliability by 2-times (Table 5).

Similarly, at $N_{200} + WSN_{1000}$, the packet overhead was decreased from 181 (for LEACH) to 98 (for MRP-FT), indicating a decrease of ca. 45.9% during t = 500 s (Figure 11, Table 5). At $N_{300} + WSN_{1000}$, the packet overhead was decreased by ca. 36.0%, which was manifested by decreased energy consumption of 134 J (by ca. 44.8%), while increased reliability by ca. 98.7% (Figure 12).

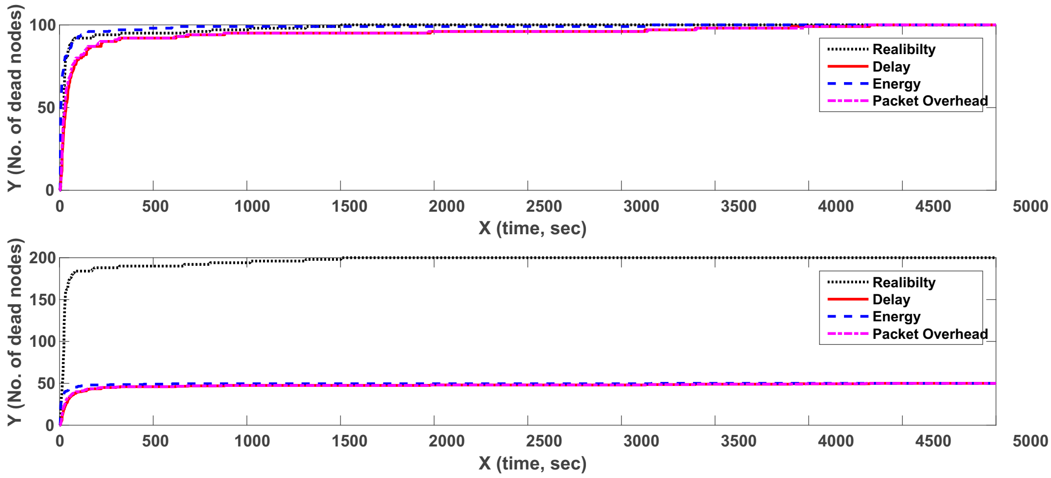

Figure 10. Comparison of reliability (in %), delay (in sec), energy consumption (in J) and packet overhead (in bytes) with existing LEACH vs. newly proposed MRP-FT protocol executed with $N_{100} + WSN_{1000}$

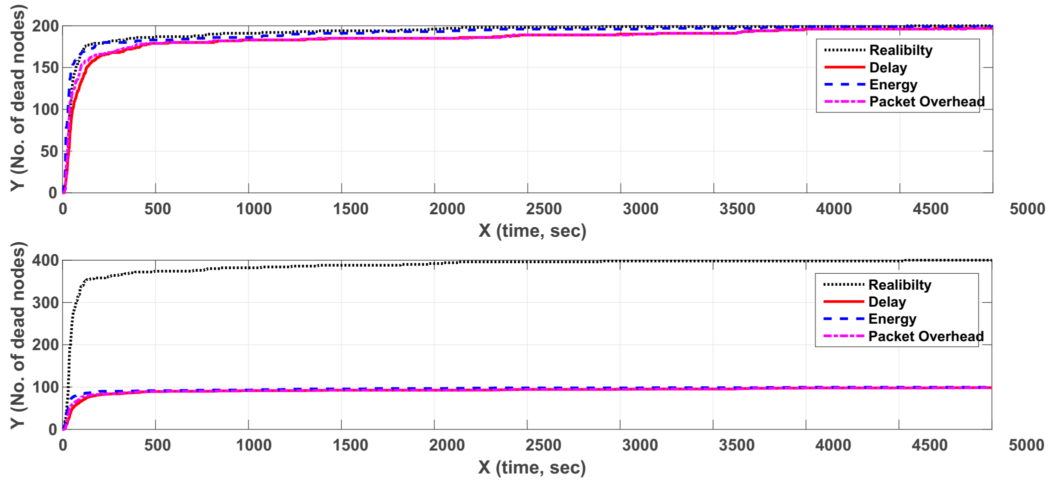

Figure 11. Comparison of reliability (in %), delay (in sec), energy consumption (in J) and packet overhead (in bytes) with existing LEACH vs. newly proposed MRP-FT protocol executed with $N_{200} + WSN_{1000}$

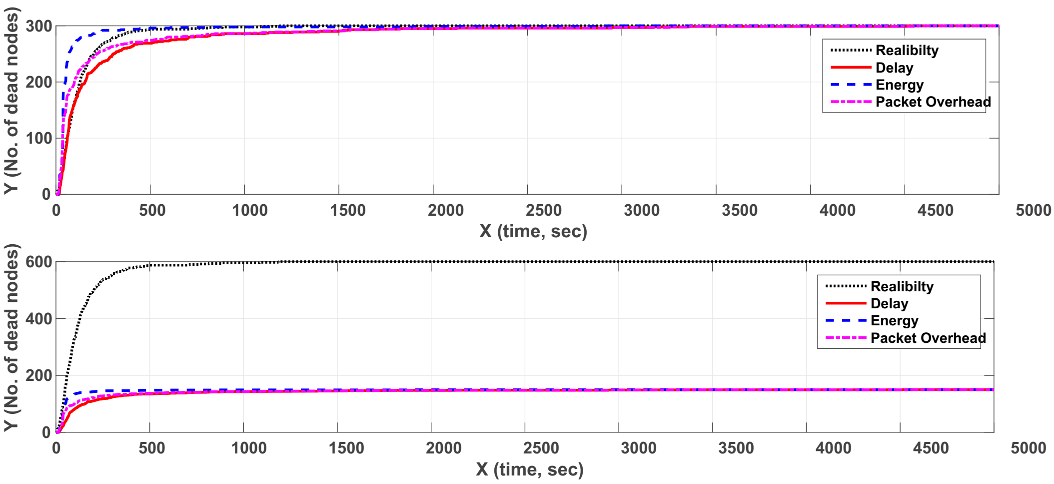

Figure 12. Comparison of reliability (in %), delay (in sec), energy consumption (in J) and packet overhead (in bytes) with existing LEACH vs. newly proposed MRP-FT protocol executed with $N_{300} + WSN_{1000}$

Table 5. Packet overhead, delay, energy and reliability at 500 s achieved with the implementation of existing LEACH protocol vs. MRP-FT executed in different combinations of number of nodes and area size and area size of 1000×1000 m^2 of WSNs

Protocol	Packet overhead	Delay (packets)	Energy [J]	Reliability [%]
LEACH (N_{100}, WSN_{1000})	89	88	94	100
MRP-FT (N_{100}, WSN_{1000})	49	48	48	200
LEACH (N_{200}, WSN_{1000})	181	179	184	194
MRP-FT (N_{200}, WSN_{1000})	98	97	98	392
LEACH (N_{300}, WSN_{1000})	272	270	299	299
MRP-FT (N_{300}, WSN_{1000})	174	173	165	594

3.5. Comparison of different WSNs for packet overheads

The results showed that increasing the area size of WSNs from WSN_{100} to WSN_{250} at N_{100} led to an increase of approximately 22.4 and 11.4% in packet overhead for the LEACH and MRP-FT protocols, respectively (Figure 13). It was important to note that similar packet overhead values were observed for both LEACH and MRP-FT protocols at N_{250} and N_{500}, which were achieved at t = 5000 s and $2500s$, respectively. This indicates that enhancing the area size of WSNs can increase their efficiency.

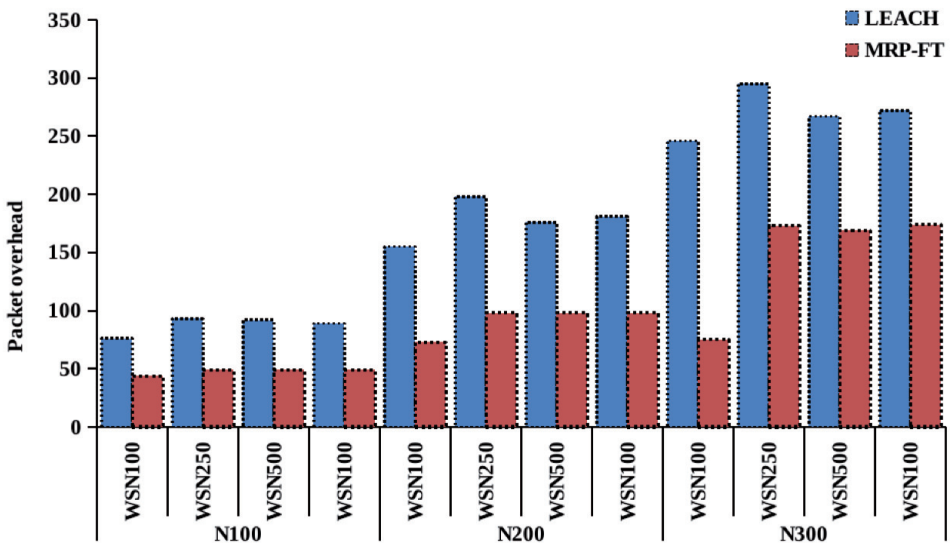

Figure 13. Inter-comparison of packet overhead simulated by using existing LEACH vs. newly proposed MRP-FT protocol executed at different combinations of numbers of inter-nodes and size of wireless sensor networks (WSNs). The values represent packet overhead simulated at t = 5000 s for N_{100} and N_{250}, t = 2500 s for N_{500} and t = 500 s for N_{1000}

When the number of inter-nodes was increased from N_{100} to N_{200}, the packet overhead almost doubled. Comparing N_{200} and N_{300}, the packet overhead simulated using the LEACH protocol increased by approximately 1.6, 1.5, 1.5, and 1.5 times at N_{300}. However, there was no change in packet overhead for $N_{200} + WSN_{100}$ and $N_{300} + WSN_{100}$. Still, a considerable increase was observed for higher WSNs area sizes $(WSN_{250-1000})$.

3.6. Relationship between different variables of WSNs

We deployed two different sensor positions, namely d_1 and d_2, to provide convenience in practical sensing. Since the diamond pattern appears to be highly complicated [14], we first deployed sensors at the endpoints of each grid using d_1 and d_2 and finally deployed a sensor at the center of each grid. Figure 14 illustrates the relationship between d_1 and d_2 for simulations made using the proposed MRP-FT protocol at different numbers of inter-nodes $(N_{100-300})$ and area sizes of WSNs $(WSN_{100-1000})$. The results showed that the value of d_1 varied between 38.3 and 382.5, while for d_2, the range was between 19.0 and 789.5. In general, the value of d_1 and d_2 increased with the area size of WSN, regardless of the number of inter-nodes. There was a significant linear relationship between d_1 and d_2 simulated using the MRP-FT protocol. The relationship between the two variables could best be described using equation

$$d_2 = 1.9651d_1 - 89.271, \quad R^2 = 0.9599^{**}; p < 0.01 \tag{6}$$

where d_1 is the position of first sensor node, while d_2 is the position of the second sensor node in WSN.

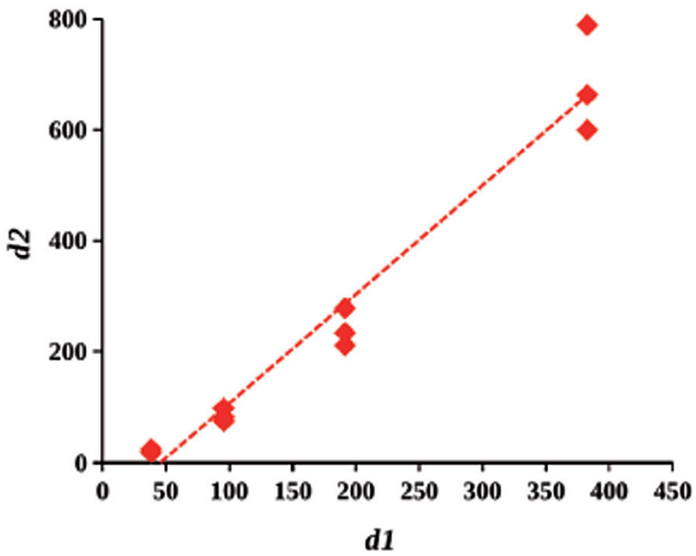

Figure 14. Relationship between the two position of sensors (d_2 vs. d_1) d to provide convenience in practical sensing for newly proposed MRP-FT protocol executed with different combinations of number of nodes $(N_{100-300})$ and area size of wireless sensor networks $(WSN_{100-1000})$

Figure 15 illustrates the number of nodes that died during sensing in different WSNs. The number of dead nodes varied between 73 and 100 for N_{100} + WSN_{100}, 160 and 200 for N_{200} + WSN_{100}, and between 239 and 300 for N_{300} + WSN_{100}. At an increased WSN area size (WSN_{250}), the number of dead nodes varied between 96–100, 196–200, and 291–300, respectively, for $N_{100} + WSN_{250}$, $N_{200} + WSN_{250}$, and $N_{300} + WSN_{250}$. These results revealed that there was not much difference in the number of dead nodes sensed using MRP-FT for WSN_{250} and WSN_{500}. However, it was important to observe a considerable change in the number of dead nodes between WSN_{500} and WSN_{1000}.The simulated results revealed that at higher WSN area size (WSN_{1000}), the number of dead nodes remained uniform, i.e., 100 for Dead-1, Dead-2, Dead-3, and Dead-4 nodes at $N_{100} + WSN_{1000}$, 199–200 at $N_{200} + WSN_{1000}$, and 297–300 nodes at $N_{300} + WSN_{1000}$.There was a significant linear relationship between the numbers of dead nodes observed for different numbers of inter-nodes $N_{100-300}$ and area sizes of WSNs $(WSN_{100-1000})$ (Figure 16). The relationship between the numbers of the first four dead nodes could best be described by equations (7)–(9).

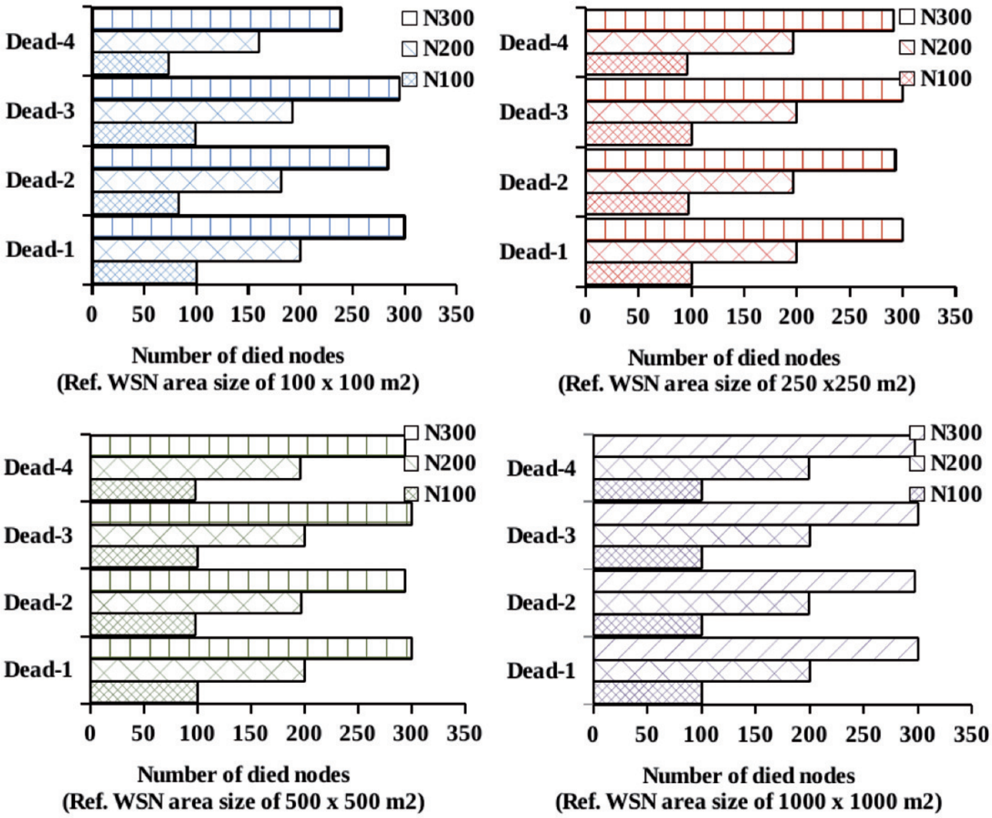

Figure 15. Number of died nodes obtained using newly proposed MRP-FT protocol executed with different combinations of number of nodes $N_{100-300}$ and area size of wireless sensor networks $(WSN_{100-1000})$

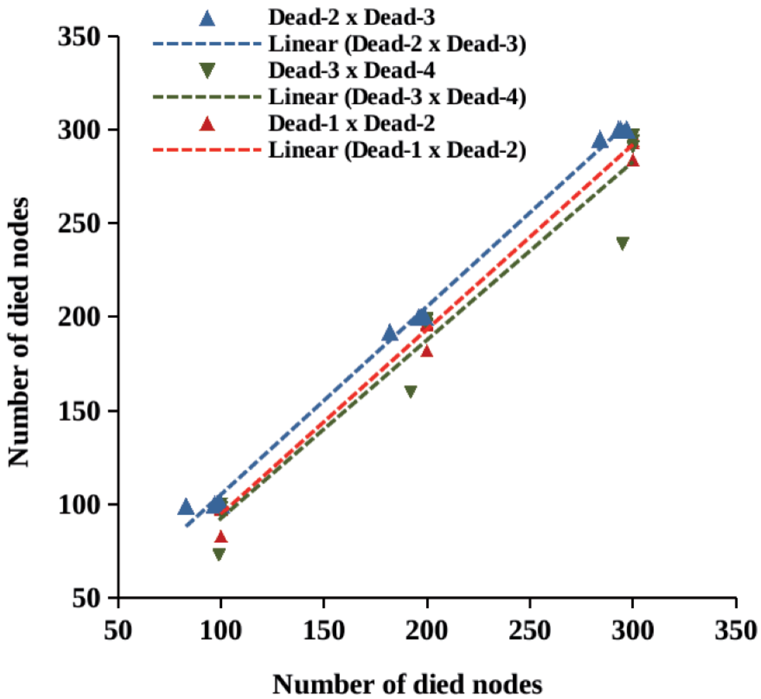

Figure 16. Relationship between number of died nodes obtained during four rounds with the implementation of newly proposed MRP-FT protocol executed with different combinations of number of nodes $N_{100-300}$ and area size of wireless sensor networks $(WSN_{100-1000})$

$$\text{Dead-1} = 0.9875\text{Dead-1} - 4.1667, \quad R^2 = 0.9942^{**},\ p < 0.01 \tag{7}$$

$$\text{Dead-2} = 1.0036\text{Dead-3} + 4.8126, \quad R^2 = 0.9969^{**},\ p < 0.01 \tag{8}$$

$$\text{Dead-3} = 0.9519\text{Dead-4} - 2.6951, \quad R^2 = 0.9595^{**},\ p < 0.01 \tag{9}$$

3.7. Relationship between packets transformed to BSs and CHs

Figure 17 depicts the correlation between the packets transmitted to the BSs and the CHs. The results demonstrate a significant linear increase in the number of packets sent to CHs as the number of packets transmitted to the BSs increases.

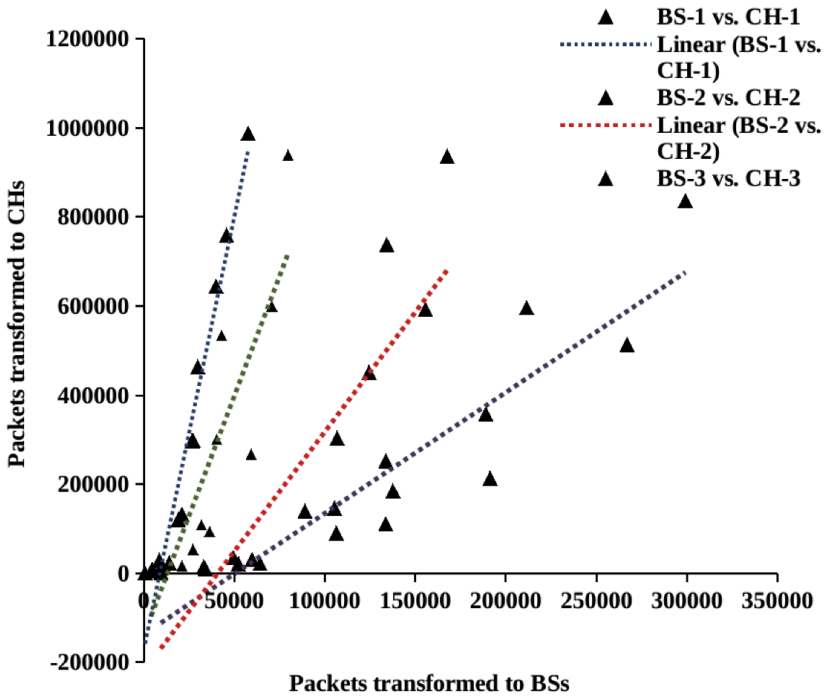

Figure 17. Relationship between packets transferred to base stations (BSs) and respective cluster heads (CHs) during the four rounds with the implementation of newly proposed MRP-FT protocol executed with different combinations of number of nodes ($N_{100-300}$) and area size of wireless sensor networks ($WSN_{100-1000}$)

The majority of the packets were transmitted to CH-1 compared to the other cluster heads. On the other hand, the number of packets transmitted to BS-4 was higher than that of the other base stations. These relationships can be represented by linear equations (equations (10)–(13).

Packets transferred to CH-1

$$P_{\text{CH-1}} = 19.465(\text{Packets transferred to BS-1}) - 172371;\ R^2 = 0.9468^{**};\ p < 0.01 \tag{10}$$

Packets transferred to CH-2

$$P_{\text{CH-2}} = 5.3728(\text{Packets transferred to BS-2}) - 219536;\ R^2 = 0.7419^{*};\ p < 0.05 \tag{11}$$

Packets transferred to CH-3

$$P_{\text{CH-3}} = 10.771(\text{Packets transferred to BS-3}) - 140657; R^2 = 0.7815^*; p < 0.05 \quad (12)$$

Packets transferred to CH-4

$$P_{\text{CH-4}} = 2.7181(\text{Packets transferred to BS-4}) - 137277; R^2 = 0.8512^*; p < 0.05 \quad (13)$$

4. Discussion

The present study compared the performance of LEACH vs. newly proposed MRP-FT protocol for heterogeneous WSNs. These results revealed substantial decrease in packet overhead by 36.0–69.5% with the implementation of MRP-FT over the existing LEACH protocol. Additionally, the MRP-FT protocol resulted in decreased energy consumption by ca. 35.9–52.9%, compared with the existing LEACH protocol [30]. These results revealed that MRP-FT protocol outperformed to realize greater extent of disjoint path as compared to the existing LEACH protocol. The results of the present study corroborate the earlier research findings [30], who reported that the fault tolerance was improved by ca. 30% when node failure rate is less than ca. 30%. The implementation of MRP-FT protocol resulted in almost two times higher reliability as compared to existing LEACH protocol. Similar to these results, it has been well established that the multi-path routing protocols has high reliability [18], load balancing [31, 55], QoS provisioning [24] and for secure communications. It is reported that node-disjoint parallel multipath routing (DPMR) protocol which applies single-hop response after a delay time at each node to construct multiple paths simultaneously, helps enhancing energy efficiency of routing protocols because the only nodes which are used by other paths forward the route requests to their neighbors [54]. Unlike, earlier results [9], who reported that as the number of nodes N increased $(N_{100-500})$, there was no change/decrease in network life time for LEACH / centralized LEACH, MOD-LEACH and SEP protocols, the network life time increased with the implementation of MRP-FT protocol in the present study. Earlier research highlighted that for a network of N_{100} and BSs located centrally, the I-LEACH protocol outperformed as compared to the LEACH protocol, with ca. 67% increase in network longevity [14]. In Energy-Efficient Multipath Routing Protocol (EEMRP), a node-disjoint multi-path protocol considers energy and hops count while constructing the multiple paths, and thereby achieve high energy efficiency without considering network reliability [55]. Similar to these results, a new technique proposed for replacing the clusters and rotating nodes with a centroid-based CH to distribute loads has shown a large scale (ca. 78%) improvement in the lifespan of the WSNs and ca. 26% improvement in overall performance [57].The constriction of k disjoint paths guarantee that a node remains connected to the sink even after the failure of up to $k-1$ paths, and consequently the disjoint paths will help improve the fault tolerance of the WSNs [27]. The fact that in Node-disjoint multi-path routing protocols which construct paths with no common nodes/links leads to strong fault tolerance, because a node failure impacts only one path, therefore, such protocols induces large control message overhead with lack of scalability [27]. The MRP-FT protocol outperforms the LEACH protocol because CHs are selected randomly, without taking into account the residual energy of the nodes for cluster formation [34]. Furthermore, the distribution of CHs in WSNs is not uniform, which can result in energy depletion as these nodes may be concentrated in a single part of the network, leading to transmission loss after aggregation and single-hop transmission to the sink node, making LEACH infeasible for large WSNs [35]. Earlier research reported that timeframe and network stability of N100 at initial energy of 5J, LEACH-MAC gave much better results as compared to the LEACH, A-LEACH, and LEACH DCS protocols [14].

Effective selection of CHs with a high energy level is critical for successful data packet transmission [58]. However, selecting CHs with insufficient energy can lead to a lack of energy for data aggregation and transmission to the sink node [56, 58]. The concept of BS mobility can enhance the lifespan of WSNs by optimizing the movement of the BSs, transforming routing from the time domain to the space domain [60]. During the first 1000 rounds of simulation, approximately 20 CHs were elected each round, and the number of elected CHs gradually decreased after 1000 rounds due to energy depletion. This result suggests that sensor nodes with appropriate energy levels are selected as CHs [2, 73, 75], allowing for balanced energy use throughout the network lifespan [75]. Fault tolerance is a critical design goal in WSNs. Multipath routing protocols are considered the most robust solution to enable efficient network operation despite faults. Therefore, the proposed MRP-FT protocol, which constructs multiple paths, enhances fault tolerance and sustainability at a reasonable cost, increasing the lifespan and resilience of the WSN [30].

5. Conclusion

The present study compared the newly proposed MRP-FT to the existing LEACH protocol under PSO-FT technique. The implementation of MRP-FT protocol significantly decreased packet overhead delay, and the energy consumption, while increasing reliability of WSNs, compared to the existing LEACH protocol. As the area size of WSNs increased (fromWSN_{100} to WSN_{250}), packet overhead increased by ca. 22.4 and 11.4% for LEACH and MRP-FT protocols, respectively, at N_{100}. The energy consumption was also considerably reduced by $35 - 123$ J with the MRP-FT protocol, compared to the LEACH protocol. The study found a significant linear relationship $(R^2 = 0.9599^{**}; p < 0.01)$ between the positions of two sensors (d_1 and d_2) deployed to provide convenience in practical sensing for the newly proposed MRP-FT protocol. These findings suggest that the MRP-FT protocol can enhance the sustainability and longevity of WSNs while providing increased resilience and fault tolerance. Therefore, these results underpin overwhelming significance of proposed networks to provide promising solution for future WSNs.

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