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Original Article

V-NRF-LEACH: An Energy-Efficient and Fault-Tolerant Clustering Protocol for Wireless Sensor Networks

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Abstract *- Wireless Sensor Networks (WSNs), composed of interconnected devices, are being deployed in industrial automation, smart infrastructures, and environmental monitoring applications. While the NRF-LEACH protocol improves network lifetime by maintaining a cluster structure across multiple rounds, its performance degrades when cluster heads fail prematurely, resulting in communication interruptions with the base station. To address this limitation, this paper offers a new variant, V-NRF-LEACH, which selects a Vice Cluster Head (VCH) based on residual energy to back up the main cluster head in case of failure to maintain continuous communication and minimize packet loss. Simulation results show that the proposed protocol significantly improves energy efficiency and network reliability compared to existing protocols and extends network lifetime. It increases the number of packets transmitted to the base station, which is important for efficient communication, by up to 35% compared to LEACH and 5% compared to NRF-LEACH.*

Keywords *- WSN, LEACH, NRF-LEACH, NRF, V-NRF-LEACH.*

1. Introduction

WSNs have become increasingly important in a wide range of application areas, such as precision agriculture, building management, healthcare, intelligent transportation, environmental monitoring, and logistics. Generally, a WSN is a collection of sensor nodes that are connected through wireless channels to gather environmental data, such as temperature and pressure, and then send the collected data to a base station for further processing. Since the sensor nodes have limited and non-rechargeable energy, energy efficiency and network lifetime remain important design challenges for WSNs.

Hierarchical routing protocols that group the network into clusters have been proposed to solve these problems and decrease energy consumption, where each cluster is controlled by a Cluster Head (CH) to gather and forward the data to the base station. The Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol [1 - 4] is among the most well-known in this category, and one round of LEACH consists of two phases: a setup phase in which clusters are created. CHs are randomly elected, and a steady-state phase in which nodes transmit data to their CHs, which then transmit aggregated data to the base station. The random election of CHs does not always ensure optimal selection, and frequent re-clustering introduces significant overhead, even though LEACH balances energy consumption among nodes.

The NRF-LEACH method was developed to enhance LEACH. By maintaining a fixed cluster structure over a Number of Rounds (NRF rounds), this variant lowers the overhead associated with reconfiguration and greatly increases network longevity and energy efficiency. NRF-LEACH does have a significant limitation, though: network performance is negatively impacted if a CH passes away too soon during its designated rounds, preventing its member nodes from communicating with the base station.

In this paper, we propose a new version of NRF-LEACH, called Vice Fixed Number of Rounds LEACH (V-NRF-LEACH), which selects a Vice Cluster Head (VCH) for each cluster to improve the fault tolerance and the reliability of communication. The VCH smoothly assumes

The role of CH is to ensure continuous communication in the event of a failure or when the energy of the CH drops below a predetermined threshold, guaranteeing continuous communication and reducing packet loss.

The following are this paper's significant contributions:

- We introduce the concept of a vice cluster head into NRF-LEACH to increase fault tolerance and improve communication reliability.
- We describe the detailed design of the V-NRFLEACH protocol, including the CH/VCH election process and operational phases.

- We evaluate the proposed approach using NS-3 simulations, comparing it with NRF-LEACH and LEACH in terms of network lifetime, energy efficiency, and packet delivery ratio.

The structure of the remainder of this article is as follows: Section 2 outlines related work, followed by a discussion of LEACH and NRF-LEACH. Section 5 introduces the adopted radio energy model. In the proposed V-NRF-LEACH approach in section 6, the simulation results are presented in section 7, and finally, a conclusion is provided in section 8.

2. Related Works

In the literature, various improvements have been proposed to the LEACH protocol to enhance the energy efficiency, load balancing, and network lifetime. These works mainly focus on optimizing Cluster Head (CH) selection, introducing backup mechanisms, or adapting cluster formation strategies.

In order to enhance energy efficiency, balance the load distribution, and increase the lifetime of WSNs, many variations of the LEACH protocol have been proposed in the literature, which mainly focus on optimizing the Cluster Head (CH) selection mechanism, introducing backup mechanisms, or adapting cluster formation strategies. In Sunhare and Chattopadhyay [7], they introduced the Controlled Cluster Networking Protocol (CCCNP), where cluster formation is controlled by cache nodes. These nodes collect data about the energy distance to the base station and location coordinates, and CHs are selected to minimize the energy consumption. Their simulation results showed that the energy, the lifespan of the far-off nodes, and the total network lifetime were improved compared to LEACH [1-4], I-LEACH [5], and LEACH-VH [6].

In [8], Kumar et al. proposed Distance and Energy Aware LEACH (DE-LEACH), where the CH selection is based on the remaining energy and the distance to the base station. The threshold formula includes the ratio of the distance of a node and the average distance of all nodes to balance the number of nodes closer to the base station to be frequently selected as the CH. Simulation results showed that DE-LEACH outperforms LEACH in terms of energy efficiency and network lifetime.

Arumugam and Ponnuchamy proposed Energy-Efficient LEACH (EE-LEACH), which uses a Gaussian distribution for sensor placement and residual energy for CH selection [9]. The data aggregation process is improved by applying the conditional probability theorem to enhance the packet delivery rate and reduce energy consumption compared to LEACH and EBRP.

Mehmood et al. introduced Vice-Head LEACH (LEACH-VH), in which each CH elects a VCH in its cluster, and the VCH becomes a CH when the energy of the CH falls below 10% of the total capacity, and a new VCH is elected [6]. This strategy enhances fault tolerance and prolongs the network's lifespan.

In another variation of V-LEACH, Aziz et al. proposed the selection of both CH and VCH based on the maximum residual energy of nodes [15]. In addition, the cooperation between CH and VCH is considered for intra- and inter-cluster communication, which gives better performance compared to V-LEACH [10-14].

Improvements to LEACH have been proposed by other researchers, including using Machine Learning to optimize the cluster formation [2], Hybrid Models combining Analytic Hierarchy Process (AHP) [16], and energy-aware versions specific to heterogeneous sensor networks [15], [18-21]. These studies support the importance of the CH election and fault tolerance in maximizing network lifetime. To summarize, Table 1 shows that existing LEACH variants focus on optimizing CH selection, increasing the reliability by backup cluster heads, or improving the cluster communication efficiency, but most methods either make the protocol more complex or add more overhead.

Table 1. Summary of LEACH variants

Protocol	Main Contribution	Mechanism	Improvement Compared to LEACH
CCCNP [7]	Cache nodes guide clustering	Residual energy, distance, and coordinates used by caches	Better residual energy, longer lifetime of distant nodes
DE-LEACH [8]	Distance & energy aware CH selection	Threshold based on residual energy + distance to BS	Longer lifetime, better energy efficiency
EE-LEACH [9]	Energy-efficient CH election & data aggregation	Residual energy + conditional probability theorem	Higher packet delivery, lower energy consumption
LEACH-VH [6]	Vice CH as backup	CH nominates VCH (switches when CH <10% energy)	Fault tolerance, longer network life
Enhanced V-LEACH [10–14]	Cooperative CH & VCH routing	CH and VCH are chosen by the maximum residual energy	Improved intra/inter-cluster communication

3. LEACH Protocol

One of the widely adopted hierarchical routing methods in WSNs is the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol. Its unpredictable, adaptive, and self-organizing characteristics help spread the energy load evenly among sensor nodes, increasing the lifespan of the network. Figure 1 shows the general layout of the LEACH technique.

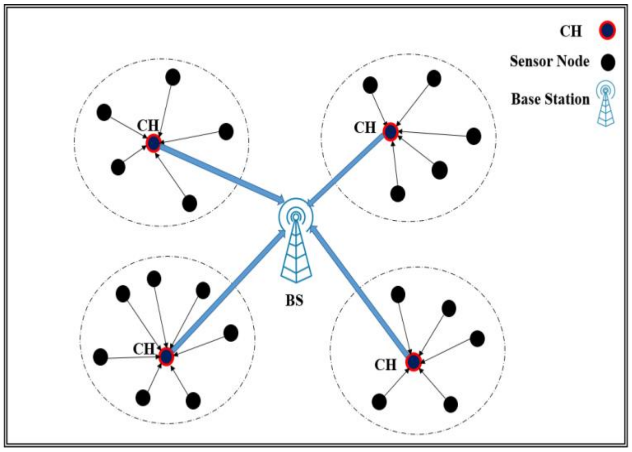

Fig. 1 The LEACH procedure is illustrated

Each round of LEACH's operations consists of two primary phases:

By producing a random number between 0 and 1, each node independently determines whether to become a Cluster Head (CH). For the duration of the current round, the node will serve as a CH if the generated number is less than a Threshold T(n). The Threshold Equation (1) is defined as follows [14-17].

$$T(n) = \begin{cases} \dfrac{p}{1 - p * (r \bmod \frac{1}{p})} & if\ n \in G \\ 0 & else \end{cases} \qquad (1)$$

Where r is the current round, p is the necessary percentage of CHs, and G is the set of nodes that have not been CHs in the preceding 1/p rounds.

Advertisement messages are sent by the chosen CHs, and non-CH nodes create clusters by joining the closest CH. To plan intra-cluster transmissions, each CH develops a TDMA schedule.

In the second phase of the permanent regime, during their designated time windows, cluster members send their sensed data to the CH. After aggregating and compressing the data, CHs send it to the base station. Each round, this process is repeated to balance the nodes' energy usage. Figure 2 illustrates the comprehensive flow of LEACH processes. By decreasing the number of nodes transmitting data straight to the base station, LEACH lowers transmission expenses. However, the protocol may occasionally choose nodes with low residual energy or unfavorable placements because of its random CH election, which could result in early failures. In addition, frequent re-clustering in every round increases overhead and energy consumption. These limitations have motivated several enhanced variants, such as NRF-LEACH and the proposed V-NRF-LEACH.

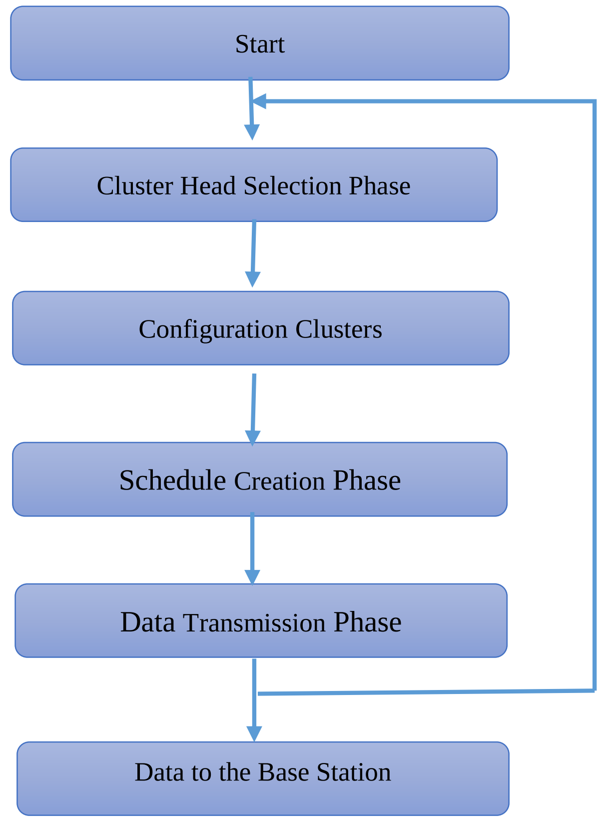

Fig. 2 LEACH protocol flowchart

4. NRF-LEACH Protocol

By adding a fixed-cluster method over several rounds referred to as NRF rounds, the NRF-LEACH protocol expands LEACH. NRF-LEACH reduces the overhead imposed by frequent re-clustering by maintaining the same cluster structure for a predetermined number of rounds, in contrast to LEACH, which reforms clusters in each round.

Like LEACH, NRF-LEACH functions in cycles made up of two phases, as seen in Figure 3:

a) Configuration Phase

- At the start of the first round of an NRF cycle, Cluster Heads (CHs) are chosen.
- Once CHs are determined, clusters are formed by associating nodes with the nearest CH.
- A transmission schedule (e.g., TDMA) is created for intra-cluster communication.

- This configuration is retained for subsequent rounds within the NRF cycle.

b) Transmission Phase

- Cluster members send their sensed data to the CHs following the predefined schedule.
- The data received is processed and aggregated by CHs before being sent to the base station.
- This process repeats during each round of the NRF cycle, with the same CHs and clusters.

Since the high cost in LEACH is energy spent in re-clustering, NRF-LEACH reduces energy consumption in re-clustering by fixing the cluster structure for multiple rounds, resulting in increased network longevity compared to the original protocol. However, there is a significant limitation in NRF-LEACH, which is that if a CH dies in the middle of its assigned NRF rounds, its cluster members cannot communicate with the base station until the following re-clustering process, which could negatively impact reliability and overall network performance, prompting our proposed enhancements to the V-NRF-LEACH protocol.

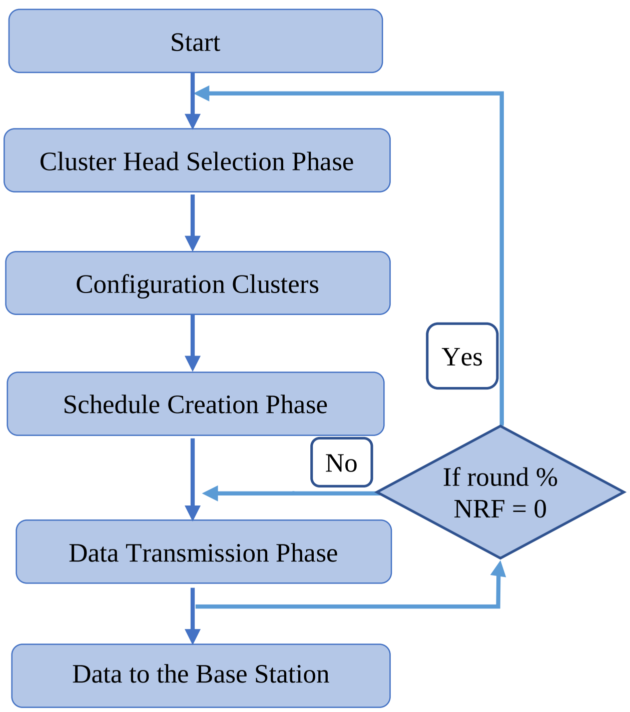

Fig. 3 NRF-LEACH protocol flowchart

Figure 3 shows how this happens: This configuration phase begins with the selection of the cluster heads, continues with the configuration of the clusters, and ends with the definition of transmission schedules; the transmission phase begins with the data sent to the cluster heads, which then combine this data and then transmit it to the base station. This data is collected and transmitted in the same manner as in LEACH, but now the cluster heads do not send data directly to the base station, as they do in LEACH. This strategy minimizes the energy consumption required to form clusters in each cycle.

5. Radio Energy Module

Energy consumption in wireless sensor networks is strongly influenced by data transmission and reception processes. The radio energy model adopted in this study follows the formulation described in [18–21]. This model distinguishes two main components: Transmission Energy (E_{Tx}) and Reception Energy (E_{Rx}), as illustrated in Figure 4.

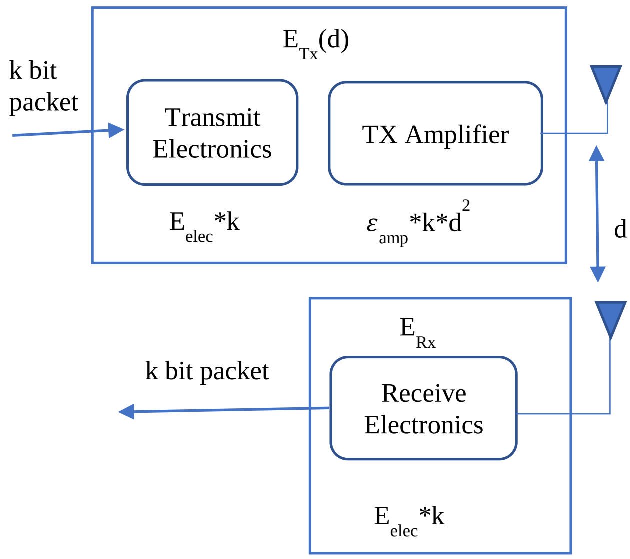

Fig. 4 Energy consumption model

When a node transmits a message of size k bits over a distance d, the energy consumption is given by Equations (2) and (3) [22-24].

$$E_{Tx}(k,d) = \begin{cases} kE_{elect} + k\varepsilon_{fs}d^2, d < d_0 \\ kE_{elect} + k\varepsilon_{amp}d^4, d \geq d_0 \end{cases} \quad (2)$$

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

Where:

- E_{elect} Is the energy dissipated to transmit or receive a single bit,
- ε_{fs} Is the propagation factor in free space,
- ε_{amp} Is the propagation factor in multipath fading,
- d_0 is the threshold distance at which the propagation model changes.

The energy needed to receive a k-bit message is represented by Equation (4) [22-24].

$$E_{Rx}(k) = k\ E_{elect} \tag{4}$$

The effect of transmission distance is highlighted by this model: Short-Range Communication (below d_0) is dominated by Loss Of Free Space (d^2). At the same time, long-range communication uses significantly more energy due to multipath Fading (d^4).

As a result, reducing the transmission distance and decreasing the number of direct communications with the base station are key strategies to improve the energy efficiency of WSNs. This is why hierarchical routing protocols such as LEACH, NRF-LEACH, and our proposed V-NRF-LEACH exist.

6. The Approach Proposed V-NRF-LEACH

Although LEACH's hierarchical clustering method provides energy balance among nodes, its random selection of Cluster Head (CH) can be an inefficient decision, as too often low residual-energy nodes are chosen. In addition, groups do not need to be reconfigured in every round.

The former problem is solved by the NRF-LEACH protocol that stabilizes the cluster structure in a few rounds, which consequently reduces the cost of re-clustering and prolongs the sensor's lifetime. However, the most significant limitation of NRF-LEACH is that if a CH fails within one round, member nodes do not communicate with the BS until the next re-clustering period, and no data transmission occurs. This results in low dependability and packet loss.

We suggest an enhanced version of NRF-LEACH called Vice Fixed Number of Rounds LEACH (V-NRF-LEACH), which adds the election of a secondary cluster head in each cluster, to get around this restriction. According to the nodes' residual energy, the VCH is chosen to serve as the CH's backup. The VCH automatically takes over as CH if the energy of a CH drops below a threshold, which is defined at 25% of the average remaining energy of its cluster, or if the CH fails. The same selection criteria are then used to designate a new VCH in the cluster. By guaranteeing continuous connectivity between nodes and the base station, this method lowers packet loss and increases.

The two primary stages of V-NRF-LEACH operation are depicted in Figure 5:

- Phase of Configuration: Clusters are constructed based on the distance between nodes and CHs after the initial cluster heads are chosen. A vice cluster head is chosen for each cluster by selecting the non-CH nodes with the largest residual energy. The VCH smoothly takes over and instantly chooses a new VCH to preserve redundancy if the CH's energy falls below 25% of the cluster's average residual energy.
- Transmission Phase: In accordance with the TDMA schedule, cluster members transmit data to the Cluster Head (or VCH if operational). The received data is combined by the CH and sent to the base station.

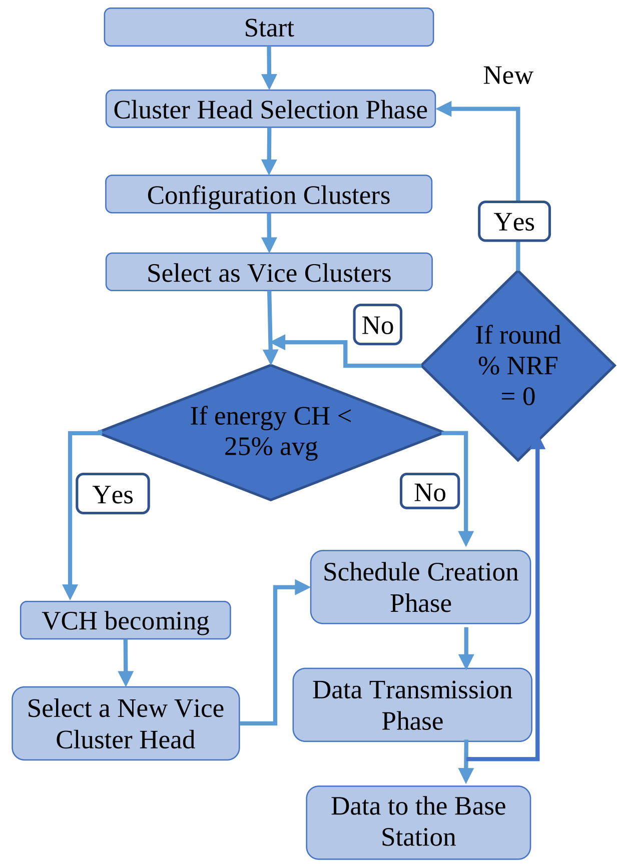

Fig. 5 V-NRF-LEACH protocol flowchart

The VCH guarantees uninterrupted data transmission in the event of a CH failure without necessitating a full re-clustering.

There are various advantages to integrating a VCH with NRF-LEACH:

Fault tolerance: even if CHs malfunction, communication is still possible.

Decreased packet loss: data interruption is reduced when a backup CH is present.

Increased network lifetime: By preventing needless re-clustering and distributing energy usage among nodes, energy efficiency is improved.

Thus, V-NRF-LEACH provides a more reliable solution for wireless sensor networks by combining the energy efficiency of NRF-LEACH with the dependability of vice cluster head processes.

7. Results and Discussion

We used the NS-3 simulator to run simulations in order to assess the suggested V-NRF-LEACH procedure. After that, V-NRF-LEACH's performance was contrasted with that of LEACH and NRF-LEACH, both of which were functioning under the same circumstances. The primary simulation parameters are summarized in Table 2.

The progression of node failures over the simulation rounds is depicted in Figure 6. In LEACH, the first node dies at round 6,281, and all nodes are dead by round 81,443. In contrast, NRF-LEACH and V-NRF-LEACH significantly delay the first node death, occurring at rounds 25,794 and 36,085, respectively. The last node dies at round 143,005 under NRF-LEACH and at round 110,573 under V-NRF-LEACH. Although NRF-LEACH achieves a slightly longer overall lifetime, V-NRF-LEACH provides greater stability in the early and middle stages, as the backup CH mechanism reduces the risk of premature packet loss.

Table 2. Simulation parameters

Parameters	Values
Size of network	100m/100m
Base Station (BS)	(102m,103m)
ε_{efs}	8 pj/bit/m2
ε_{amp}	0.0013pj/bit/m4
E_{elec}	50 nj/bit
d_0	87.7 m
Initial Energy	0.5 j
Cluster Head probability	0.05
Total nodes	100
Schedule Message	16 bits
Message Length	32bits
NRF	6

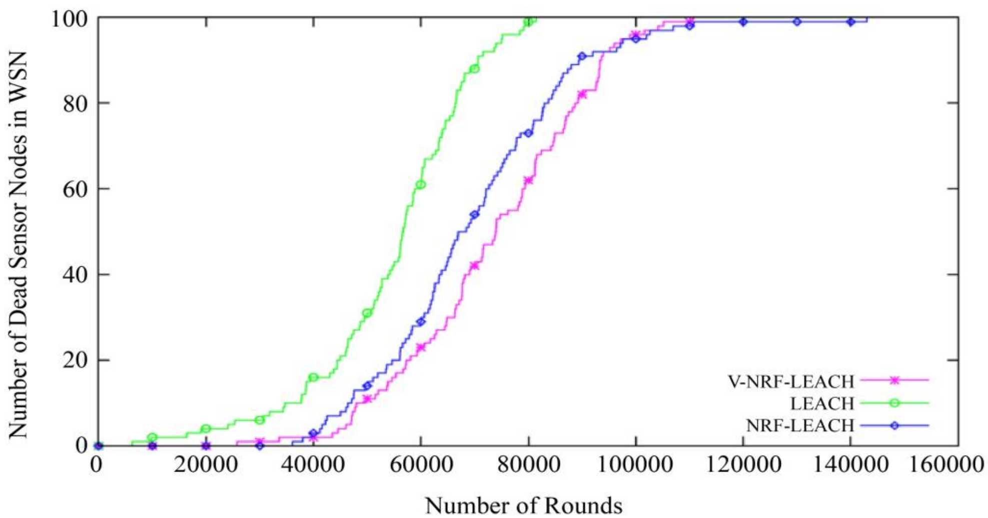

Fig. 6 The quantity of dead nodes over the rounds

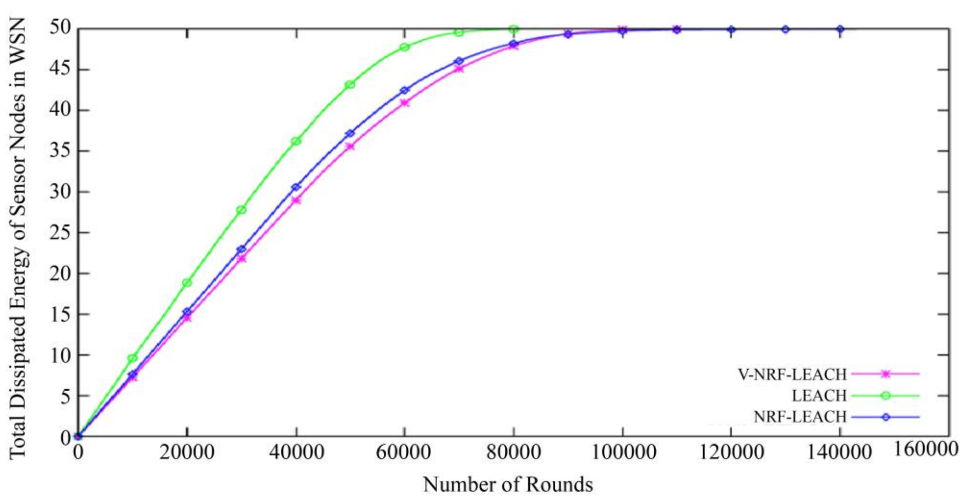

Fig. 7 Total energy lost by sensor nodes in a wireless sensor network

Figure 8 compares the number of packets successfully delivered to the base station. LEACH achieves a total of 174,676,000 packets, NRF-LEACH delivers 221,977,000 packets, while V-NRF-LEACH achieves the highest value with 234,754,000 packets. This represents an improvement of 34.39% over LEACH and 5.75% over NRF-LEACH. These results confirm that, despite a slightly shorter total lifetime than NRF-LEACH, V-NRF-LEACH ensures more reliable data delivery due to its backup CH mechanism, which prevents data loss when primary CHs fail.

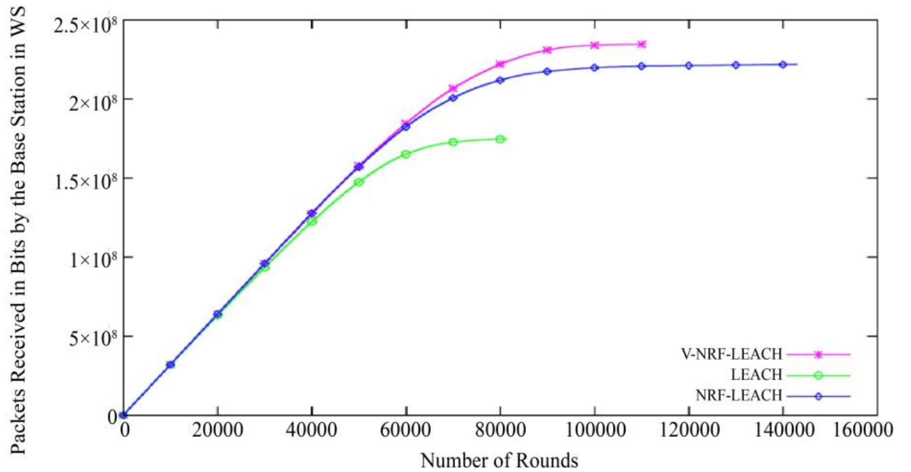

Fig. 8 Packets received by the base station in the WSN

The results show that both NRF-LEACH and V-NRF-LEACH improved the performance of sensor networks better than LEACH. It saves energy and prolongs the life of the network, and V-NRF-LEACH improves network reliability by handling failures and constantly sending data, reducing packet loss. More information reaches the base station. The downside is that V-NRF-LEACH requires more energy to maintain vice-cluster heads, so the network lifetime is lower than NRF-LEACH. Overall, V-NRF-LEACH is a compromise that provides a reliable, energy-efficient network with a constant flow of data.

8. Conclusion

WSNs are increasingly deployed in various applications, but their performance remains limited by the limited and non-replaceable energy of sensor nodes. To solve this problem, cluster-based protocols such as LEACH and its variants have been proposed. While LEACH provides an efficient baseline for energy balancing, its frequent re-clustering and random CH selection reduce its reliability. NRF-LEACH improves the efficiency by fixing the cluster structure in several rounds. However, its main limitation is the premature failure of the CH, which disrupts the interaction between cluster members and the base station. In this work, we propose V-NRF-LEACH, an improved version of NRF-LEACH that introduces a VCH. The selection is based on the energy that remains. When the primary CH fails, or the energy drops below a predefined threshold. This mechanism makes sure/ensures that communication is continuous and that packet loss is minimized without the need for immediate re-clustering. The performance of the system is significantly improved by V-NRF-LEACH in comparison to LEACH and NRF-LEACH, as shown by the simulation results. Compared to LEACH, it increases the number of packets delivered to the base station by 34.39%, and compared to NRF-LEACH, it increases the number by 5.75%. While the NRF-LEACH approach does result in a marginal increase in the overall network lifespan, the V-NRF-LEACH method offers enhanced reliability and fault tolerance, resulting in more efficient data delivery during network operation. In spite of these promising results, V-NRF-LEACH does have its limitations. The protocol introduces a modest overhead due to the maintenance of vice cluster heads, and scalability to larger or heterogeneous networks has not been fully evaluated. In addition, issues such as node mobility, dynamic environments, and security against malicious attacks remain open challenges. Future work will focus on extending V-NRF-LEACH to support heterogeneous WSNs and mobile nodes, integrating machine learning–based CH/VCH selection strategies, and incorporating lightweight security mechanisms to enhance resilience in practical IoT environments.

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