The Performance of Stable Zones Protocol for Heterogeneous Wireless Sensor Networks

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Received: 2 May 2024 | Revised: 4 June 2024 | Accepted: 7 June 2024

DOI: https://doi.org/10.48084/etasr.7716

ABSTRACT

Wireless sensor networks are characterized by significant constraints, with the primary performance parameter being their lifetime. In the context of a wireless sensor network, the distance from the base station emerges as a critical factor that influences the energy consumption of the nodes, thus affecting the overall network lifetime. To address this issue, this study introduces the Stable Zones Protocol for Heterogeneous wireless sensor networks (SZP-H). This protocol strategically divides the network into distinct zones, each differing from the other in terms of its distance from the base station and the initial energy available. This protocol outperformed traditional protocols, effectively mitigating the challenges associated with node energy consumption and improving the overall performance of the wireless sensor network. The simulation results show that SZP-H achieves the highest possible stable period and lifetime and the highest throughput level compared to the FBECS, E-CAFL, and LEACH-FC protocols. Specifically, SZP-H achieves a remarkable extension of the network's lifetime by a ratio of 303%, and 275% compared to FBECS, E-CAFL, and LEACH-FC.

Keywords-heterogeneous wireless sensor networks; routing protocols; stable zones; lifetime; latency

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are distinct networks characterized by unique criteria, such as battery-powered nodes, making energy a critical parameter [1]. These networks face limitations in processing capacity and transmission range and are often deployed in challenging areas where maintenance is difficult [2]. Routing protocols are crucial for WSNs to extend their lifetime while maintaining network integrity for successful application execution [3, 4]. WSNs typically consist of a Base Station (BS) and several clusters that exchange data, managed by routing protocols to optimize paths for efficient data transmission with minimal energy consumption [4, 5]. These protocols can be classified into clustering and non-clustering approaches, single-hop and multi-hop mechanisms, and tailored for homogeneous or heterogeneous WSNs, the latter depending on nodes' initial energy levels [6]. Current routing protocols for WSNs include:

- LEACH (Low-Energy Adaptive Clustering Hierarchy), which is a popular clustering-based protocol that aims to extend network lifetime by forming clusters and rotating cluster heads to distribute energy among sensor nodes.
- SEP (Stable Election Protocol) is an extension of LEACH that uses a probabilistic approach to select Cluster Heads (CHs) to achieve stability and balance energy consumption.
- TEEN (Threshold-sensitive Energy Efficient Sensor Network) is an event-driven routing protocol that adjusts data transmission rate using a threshold-based mechanism to optimize energy consumption and network lifetime.
- AODV (Ad-hoc On-Demand Distance Vector) is an on-demand routing protocol that establishes routes as needed, utilizing distance vector routing and route discovery techniques in dynamic network environments.
- DSR (Dynamic Source Routing) is a reactive routing protocol that relies on source routing, including the complete route in the packet header to reduce overhead by maintaining fewer routing table entries but incurring higher per-packet overhead.

- CBR (Cluster-Based Routing) is a hierarchical routing protocol that organizes sensor nodes into clusters, using cluster heads for inter-cluster communication and reducing energy consumption by aggregating data within clusters.
- MTE (Multi-hop Topology control and Energy-balanced routing) is a hybrid routing protocol that combines topology control and routing, adjusting transmission power levels and selecting energy-balanced routes to optimize network lifetime.

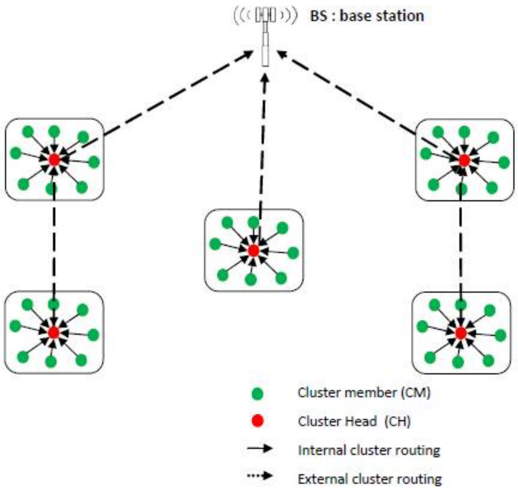

Fig. 1. Structure of a WSN network.

Designing routing protocols for WSNs is challenging due to inherent constraints. Routing protocols can be categorized according to network topology or node types and distributions. This study focuses on zone-based topologies, emphasizing heterogeneous nodes within these zones. In [7], a Zone-Based Routing Protocol (ZBRP) was introduced, using clustering to enhance sensor network lifetime by minimizing energy consumption and control overhead. ZBRP employs location information and random back-off timers for CH designation, promoting uniform energy consumption. The Ring-Zone Routing (RARZ) protocol, proposed in [8], is a location-based, multi-hop energy-efficient protocol that divides the network into concentric rings around the BS, with the inner ring nodes acting as data carriers for the outer rings. RARZ outperforms AIMRP, AODV, and Flooding in end-to-end delay, average hop count, and energy consumption. In [9], a protocol was introduced that divided the network into three circular zones with homogeneous nodes. Each zone independently selected CHs to relay data to the BS, initially favoring CHs from the same subzone. The SEP protocol [10] effectively manages heterogeneity. Z-SEP [11] extends the SEP by dividing the network into multiple zones and deploying advanced nodes in the farthest zone. AZ-SEP [12] further manages the advanced zone using a multi-hop communication approach.

The Z-SEP protocol is more suitable in heterogeneous WSNs as it divides the network into multiple zones, with advanced nodes strategically placed in the outermost zone [11]. The AZ-SEP protocol improves this by managing the advanced zone with a multi-hop communication approach for data transmission to the BS [12]. LEACH-L also investigates multi-hop communication by defining a maximum distance parameter to determine the most suitable communication method [13]. Nodes within a certain distance to the BS use one-hop communication, while those farther away use multi-hop communication. The HZ-SEP network architecture divides sensor nodes into two regions based on a threshold distance. Homogeneous nodes, closer to the BS, belong to Region 1 and transmit data directly to the BS or gateway node. Heterogeneous nodes, farther from the BS, are in Region 2 and transmit data to the gateway node, which aggregates data before sending them to the BS. The leader nodes in both regions are elected based on remaining energy. The nodes transmit data based on an energy threshold and enter sleep mode to conserve energy when below this threshold.

This study aims to address the lack of methods for determining node heterogeneity levels, defining them to maximize WSN performance. Challenges for routing in stable heterogeneous zones include:

- Managing heterogeneous nodes with varying capacities.
- Forming stable zones with similar node characteristics and dynamic adjustment.
- Ensuring scalability to handle large node numbers and efficient data routing.
- Optimizing energy consumption while maintaining reliable communication.
- Providing fault tolerance, route repair, and adaptation to network dynamics [14].
- Addressing privacy concerns, node authentication, and data integrity in hostile environments [15].

This study introduces the Stable Zones Protocol for Heterogeneous WSNs (SZP-H) and provides simulation and performance results. SZP-H is a one-hop, non-clustering protocol optimized for network performance. The topology is divided into two zones, each with multiple nodes to ensure comprehensive coverage. Nodes within the same zone have homogeneous initial energy levels, while nodes in different zones show heterogeneity. The degree of heterogeneity is examined and validated, demonstrating how SZP-H effectively manages the varying energy levels between the nodes within the heterogeneous WSN.

II. NETWORK AND ENERGY MODELS

The WSN under investigation is characterized by a two-zone structure, denoted as Z_0 and Z_1. Z_0 is identified as the internal zone, while Z_1 is designated as the external zone. Each zone comprises a total of 50 nodes (N). Within a given zone, nodes are considered homogeneous and share the same level of energy E. Specifically, nodes in Z_0 are equipped with batteries having a capacity of 0.5 J. In contrast, nodes in Z_1 possess an alpha extra energy compared to their counterparts in Z_0, with the energy denoted as $(E = 0.5 + alpha)$. This distinction in energy levels between the internal and external zones introduces controlled heterogeneity, which is a key factor in evaluating the performance of the proposed SZP-H protocol.

The energy model used in this study is based on the established LEACH model. This model takes into account various processes inherent in a clustering-based topology, distinguishing between the roles of nodes as CHs or cluster members. The different scenarios involve nodes participating in transmission, reception, or data aggregation, summarized as follows.

- Equation (1) represents the transmission equation, which depends on whether the distance is less than or equal to d_0.
- Equations (3) and (4) correspond to the reception and aggregation equations, respectively. These equations collectively capture the energy dynamics associated with the diverse activities carried out by the nodes in the network, forming the basis for evaluating energy consumption and efficiency in the context of the proposed SZP-H protocol. Table I shows the rest parameters.

$$E_{Tx} = \begin{cases} L.E_{elec} + L.\varepsilon_{fs}.d^2, \ if\ d \le d_0 \\ L.E_{elec} + L.\varepsilon_{mp}.d^4, \ if\ d > d_0 \end{cases} \quad (1)$$

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \quad (2)$$

$$E_{Rx} = L.E_{elec} \quad (3)$$

$$E_{DA} = L.E_a \quad (4)$$

TABLE I. LEACH ENERGY MODEL PARAMETERS

Parameter	**Abbreviation**	**Values**
E_{Tx}	Energy consumed in emission	Calculated by (1).
E_{Rx}	Energy consumed in reception	Calculated by (3)
E_A	Energy consumed in data aggregation	Calculated by (4)
p_s	Packet's size	4000 bits
n_p	Number of packets	[1..n]
E_{elec}	Energy dissipated per bit to run the transmitter or the receiver circuit	50 n_j/bit
E_a	Energy consumed in data aggregation bit per signal	5 n_j/bit/signal.
E_{fs}	Transmitter amplifier, energy-free space model	10 p_j/bit/m^2
E_{mp}	Transmitter amplifier energy multipath model	0.0013 p_j/bit/m^4
d	Distance either to the BS or a CH	[1..d_0] m
d_0	Calculated using (2)	≈ 87.7 m

III. CONFIGURATION AND EVALUATION

The choices made to configure the SZP-H were thoroughly analyzed and validated. This includes a detailed exploration of the rationale behind the selected parameters, their individual significance, and their collective impact on the overall performance of the protocol within heterogeneous WSNs. The goal is to provide a solid foundation for understanding the key elements that contribute to the effectiveness of SZP-H. Figures 3 and 4 illustrate the energy consumption patterns of a node across the WSN, ranging from zero to the farthest point from the BS in the network denoted, as d_{max}. The calculation for d_{max} is determined by (5).

$$d_{max} = \sqrt{x_{BS}^2 + y_{BS}^2} \quad (5)$$

where d_{max} represents the maximum distance, x_{BS} is the x-coordinate of the BS, and y_{BS} is its y-coordinate. The d_{max} parameter is crucial in the spatial coverage of the network and sets the stage for further investigation of the energy dynamics of nodes at varying distances within the network architecture. Figures 2 and 3 provide insights into how node energy consumption and a WSN's lifetime vary as a function of distance, respectively, shedding light on the implications of the alpha-energy addition in the second zone.

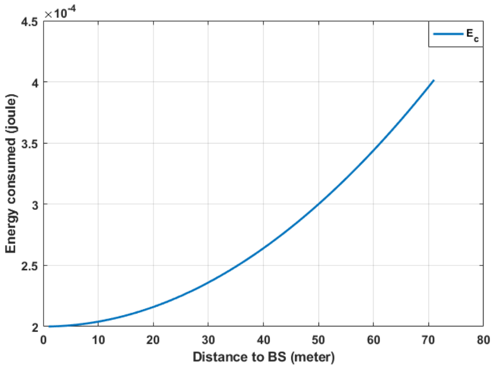

Fig. 2. Nodes' energy consumption vs distance to the BS.

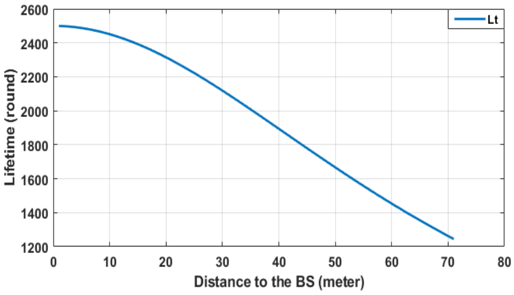

Fig. 3. Nodes' lifetime vs distance to the BS.

Based on the results obtained, it is observed that the lifetime of nearby nodes can reach up to 2500 rounds, while nodes situated at the farthest distances experience a lifetime of approximately 1250 rounds, roughly half of the lifetime of the close nodes. These findings underscore the importance of considering the impact of heterogeneous zones on network longevity. Moreover, the analysis reveals that the energy consumption to transmit data increases significantly with distance. For instance, the energy consumed for sending data from a distance of 71 m is approximately twice that consumed for a distance of one meter. This observation is notable for optimizing energy efficiency and performance in network communication. In the internal zone Z_0 of this network topology, close distances are approximately 1 m, with the furthest distance being 35.36 m. Conversely, in the external zone (Z_1), the closest proximity to the BS is approximately 36 m, and the furthest distance extends to 71 m. Understanding these distance variations is crucial for designing and implementing effective protocols, such as the proposed SZP-H, that account for the diverse energy consumption patterns within a heterogeneous network. Introducing alpha energy involves ensuring synchronization among the nodes in the network.

This study adopted a deliberate approach by selecting the first node from each zone as the reference point for synchronization. By doing so, the extra energy level to be added is determined based on the energy level of these chosen initial nodes. Consequently, this synchronization strategy establishes a baseline for the energy levels within the zones, with subsequent nodes in each zone following the lead of their respective first nodes. This approach contributes to a more uniform and controlled energy distribution throughout the network, optimizing the overall performance of the proposed SZP-H protocol. Hence, the additional alpha energy represents the energy increment allocated to the initial node in the external zone, ensuring that its packet contribution aligns with that of the initial node in the internal zone. This relationship can be expressed through the following equations:

$$L(Z_0) = L(Z_1) \tag{7}$$

$$\frac{Ei}{Ec(1)} = \frac{Ej}{Ec(36)}, \text{ thus } E_j = 36 \text{ J} \tag{8}$$

where $L(Z_0)$ represents the lifetime of the initial node in the internal zone, $L(Z_1)$ represents the lifetime of the initial node in the external zone, Ei and Ej denote the initial energies of the first nodes ($Ei = 0.5$, $Ej = 0.63$), and $Ec(1)$ and $Ec(36)$ indicate the energy consumed by initial nodes in each zone at 1 and 36 m distance from the BS, respectively.

ALGORITHM 1: SZP-H PROTOCOL

```
BEGIN
BS.broadCast("start message");
for all node(i) do
  node(i).getDistToSink;
  node(i).sendToSink(node(i).dToSink);
end for
ZHs.selectMinDist;
ZHs.broadCast(minDist);
for all node(i) do
  node(i).sendingRate = enrTx(node(i).dToSink) /
    enrTx(minDist);
  node(i).sendingRateVar = node(i).sendingRate;
end for
while exist an alive node(i) do
  for all node(i) do
    if (node(i).sendingRateVar >= 1) then
      node(i).sendPacket(cd); // cd: collected data
      node(i).sendingRateVar = node(i).sendingRateVar
        - 1;
    else
      node(i).sendingRateVar = node(i).sendingRateVar
        + node(i).sendingRate;
    end if;
  end for
end while
END
```

The SZP-H protocol is a non-clustering, one-hop protocol designed for heterogeneous nodes. Nodes within the same zone initiate the simulation with an equal amount of energy. The degree of heterogeneity is systematically examined based on the distance of each zone from the BS. The SZP-H algorithm is outlined in the steps provided below:

- For each zone, get the distance to the BS.
- For each node, take its initial energy ($Z_0 = 0.5$ J and $Z1 = 0.63$ J).
- Each node synchronizes with the closest node in its zone.
- Each node gets its rate of sending data to the BS.
- Each node sends the collected data according to its rate till it runs out of energy.

Algorithm I shows the main steps of the SZP-H.

Figure 4 illustrates the simulated topology, with the internal zone delineated by red borders and the external zone depicted in blue, each containing 50 nodes. The simulated topology is represented by two rectangular zones, equal in size and containing 50 nodes. This setup ensures the formation of two similar zones but with different conditions, such as distance to the BS, which will be addressed by the heterogeneity level of nodes' initial energy.

TABLE II. NETWORK PARAMETERS

Parameter	Value
Network area	100×100 m
Number of nodes	100 nodes
Number of zones	2
Internal zone (Z0)	70×70 m
External zone (Z1)	100×100 m / 70×70 m
Number of nodes per zone	50 nodes

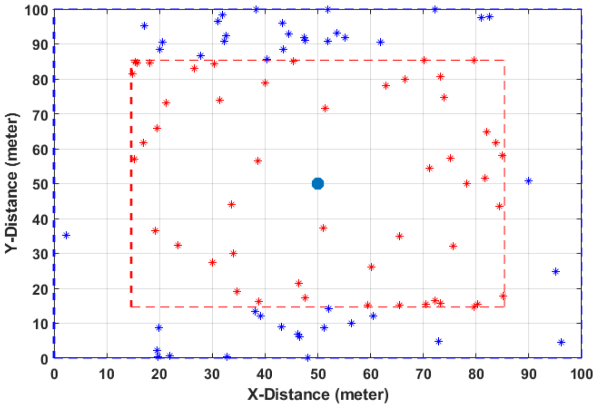

Fig. 4. The simulated network topology.

Figures 5 and 6 present a comparative analysis of the lifetime and throughput of the proposed SZP-H in contrast to LEACH-FC [16], FBECS [17], and E-CAFL [15], respectively. The implementation of the SZP-H protocol results in a higher number of packets transferred from network nodes to the BS compared to the other protocols. Tables III and IV show the FDN, HDN, and LDN values and the advances in the context of the SZP-H compared to the LEACH-FC, FBECS, and E-CAFL protocols. Table IV shows that the proposed SZP-H surpasses the other networks by 303.0%, 303.0%, and 275.8% for the FDN parameter. Additionally, SZP-H outperforms the others in HDN by 261.1%, 241.6%, 251.4%, and in LDN by 243.1%, 235.1%, and 230.4%, respectively.

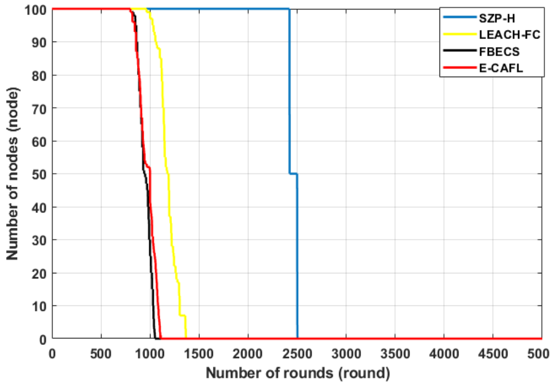

Fig. 5. Network lifetime.

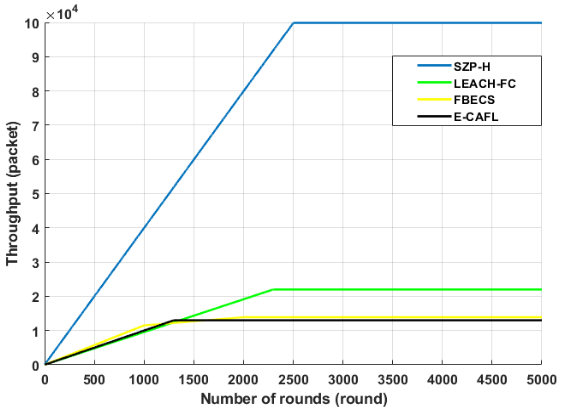

Fig. 6. Network throughput.

TABLE III. FDN, HDN, AND LDN FOR SIMULATED PROTOCOLS

Protocol	FDN	HDN	LDN
FBECS	800	940	1030
E-CAFL	800	1020	1065
LEACH-FC	879	980	1087
SZP-H	2424	2464	2504

TABLE IV. PERFORMANCE COMPARISON

Protocol	FDN	HDN	LDN
FBECS	303.0 %	262.1 %	243.1 %
E-CAFL	303.0 %	241.6 %	235.1 %
LEACH-FC	275.8 %	251.4 %	230.4 %

The simulation results underscore that the adoption of the SZP-H protocol enhances the efficiency of the network to its highest potential. This efficiency is evident in both the extended lifespan of the network and the increased number of packets successfully transmitted to the BS. In addition, as confirmed in other studies, the clustering algorithm is implemented to concurrently minimize the intra-cluster distance along with optimizing the usage of network energy.

IV. CONCLUSION

This study introduced the SZP-H protocol for heterogeneous WSNs. The proposed protocol demonstrated remarkable success in extending the network lifetime, achieving improvements of 303 and 275% compared to the FBECS, E-CAFL, and LEACH-FC protocols. Additionally, a method for determining the level of heterogeneity with multiple zones was presented. For a network consisting of two zones, where nodes in the first zone possess an initial energy of 0.5 J, this approach revealed that the extra alpha energy required for the second external zone is 0.13 J, representing a 26 % increase. As discussed previously, the degree of heterogeneity is intricately linked to the number of zones in the network and the distance of each zone to the BS. Compared to previous protocols based on the heterogeneity level of the nodes, this approach obtains the energy percentage to each zone according to their distance to the BS, providing a formula for getting the zones' heterogeneity level. Looking ahead, future research efforts could delve into a more detailed exploration of heterogeneity in WSNs. This involves considering various nuances such as cluster or non-cluster-based protocols and the data transfer mechanism to the BS (one- and multi-hop), providing a more comprehensive understanding of heterogeneity's impact on network performance.

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