Z-MSP: Zonal-Max Stable Protocol for Wireless Sensor Networks

Ahmed Harbouche
LIA Laboratory, FSEI, Hassiba Benbouali University of Chlef, Algeria
a.harbouche@univ-chlef.dz

Djamal Djabour
LIA Laboratory, FSEI, Hassiba Benbouali University of Chlef, Algeria | LSC Laboratory, National Engineering School of Tunis, University Tunis Manar, Tunisia
d.djabour@univ-chlef.dz (corresponding author)

Amine Saiah
LIA Laboratory, FSEI, Hassiba Benbouali University of Chlef, Algeria
a.saiah@hotmail.com

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ABSTRACT

Clustering is a well-known energy enhancement approach used to prolong the lifetime of Wireless Sensor Networks (WSNs). However, it introduces another issue, which is the selection of the optimum number of clusters along with the appropriate cluster heads. In this paper, we study in detail the clustering approach and its impact on enhancing WSN lifetime. We provide a mathematical study that discusses the impact of clustering, where the WSN is divided into multiple zones, each zone functioning as an independent cluster. The WSN topology consists of 10 zones, all similar in area and density but differing in their distances to the base station. To prolong the WSN's lifetime, we developed Z-MSP, an extension of MSP for Zonal WSNs. It maintains the highest stable period of MSP for the Z-WSN. Z-MSP prolongs the network's stable period by 315.625%, 315.625%, and 287.258%, and the lifetime by 245.340%, 237.277%, and 232.475%, with a very high throughput level compared to FBECS, E-CAFL, and LEACH-FC, respectively.

Keywords-wireless sesnor networks; zone; cluster; enerrgy efficiency; lifetime; throughput

I. INTRODUCTION

A Wireless Sensor Network (WSN) is a highly constrained network. A WSN is a set of sensor nodes. A node is composed of sensing, processing, energy, and communication units. They mainly suffer of their limited energy which defines their lifetime period [1, 2]. WSNs are mostly used in hostile environments where batteries are unchangeable [2]. Theoretically, the communications are the main reason behind the batteries' drain [3]. So, an energy-efficient routing protocol is a real need for such constrained networks [4]. Routing protocols in WSNs are designed for many purposes such that lifetime enhancement, fault tolerance, application needs [5, 6], etc. In this work, we focus on the energy-enhancement type, especially, cluster-based once, starting from the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol [7], which is the root of energy enhancement protocols. It is a one hop cluster-based protocol for homogeneous WSNs. LEACH considers the clustering as the main approach to optimize the consumed energy. However, it uses a random selection for clusters heads with a threshold value. LEACH has inspired numerous protocols with a shared principle: the recognition that clustering can significantly enhance the lifespan of a network [8, 9]. While clustering nodes into clusters, the zonal concept offers an alternative approach by dividing the network area into distinct zones, each varying in node density and area coverage [10]. Moreover, clustering can be implemented within zones, where a protocol may feature an area comprised of multiple zones [11, 12]. In such cases, nodes form clusters to transmit their data, cluster heads aggregate the data from their members, and subsequently relay it to the base station (BS), either in a single hop or multiple hops [12, 15].

In [16], an improved energy-efficient routing protocol is introduced for Heterogeneous Wireless Sensor Networks (HWSNs). Initially, the protocol assumes that different types of nodes are distributed among different zones. It then improves the criteria for choosing cluster chiefs by giving preference to nodes that have more remaining energy. Authors in [17] introduced the Enhanced Zonal Stable Election Protocol (EZ-SEP), a routing protocol for HWSNs that is intended to handle heterogeneity. This protocol uses a hybrid approach to connect sensor nodes to the Base Station (BS). Some nodes communicate with the BS directly, while the rest of the nodes use a clustering technique to provide data.

In this manuscript, we introduce the Zonal-Max Stable Protocol (Z-MSP), which explores the zonal-partitioning approach within the framework of the LEACH energy model. Z-MSP is derived from the MSP protocol [18], renowned for maximizing the lifetime of WSNs. Our Z-MSP retains the performance of MSP while operating within a zonal network environment. To achieve this, we conduct an extensive examination of zone utilization in WSNs. Initially, we delve into the efficient division of the network area into zones.

II. RELATED WORK

Routing protocols for WSNs garner significant interest among researchers, constituting a fundamental aspect of WSN management due to their pivotal role in handling network traffic. Their primary objective is to optimize traffic management to extend the WSN's operational lifespan as much as possible. Routing protocols that surpass the expected WSN lifespan are termed energy-based enhancement protocols, primarily because the commonly used definition of WSN lifespan is tied to the lifespan of its initial node. Achieving an extended operational period for a WSN is a topic rich in scholarly exploration, with researchers delving into various approaches. Routing protocols are categorized into numerous classes, such as clustering-based, zonal-based, and application-based protocols. In this section, our focus lies predominantly on zonal-based protocols.

The concept of zonal protocols originates from the Zonal-Stable Election Protocol (Z-SEP) [11], which is essentially a zonal adaptation of the Stable Election Protocol (SEP) [13]. SEP, in turn, represents an upgraded iteration of the LEACH protocol [7], which serves as the foundational framework for routing protocols in WSNs. Z-SEP partitions the WSN's area into three distinct zones. The first zone encompasses the region surrounding the base station, flanked by two outer zones. Nodes within the first zone transmit their data directly to the BS, while nodes in the remaining zones organize into one-hop clusters, with Cluster Heads (CHs) relaying the aggregated data directly to the BS. Nodes in the outer zones typically possess a higher energy level compared to those in the proximal zone (i.e., the first zone). AZ-SEP (Advanced Zonal-Stable Election Protocol) for WSNs [12], an extension of its predecessors Z-SEP and SEP, embodies the culmination of their advancements. The creators of AZ-SEP present a comprehensive routing protocol offering various options to minimize energy consumption and extend the lifetime of WSNs. Notably, AZ-SEP builds upon Z-SEP by introducing multi-hop communication between clusters in the two distant zones, thereby enhancing its efficiency and effectiveness. ZSEP-E (Zone-Based Clustering Protocol for Wireless Sensor Networks) operates on a zone-based approach. This protocol involves deploying energy-level nodes of a specific type, starting from the BS location. Within the network area, clusters are formed within rectangular zones, and the selection of CHs is based on a probabilistic algorithm that considers the weighted residual energy of nodes relative to others within their respective zones. This approach results in the formation of dense clusters localized within the zones. The main concept behind ZSEP-E is to partition the network area into rectangular zones, with the number of elected CHs being determined based on the number of nodes and the size of the zone.

Authors in [19] propose the improved Zonal-Stable Election Protocol (ZSEP) algorithm and partition communication ranges into three zones. They randomly deploy regular sensor nodes in the central zone and advanced sensor nodes in the remaining two zones, aiming to improve energy efficiency. They also use a method from homogeneous WSNs to improve cluster election and extend the WSN’s lifetime. QBCR (Quadrangle Based Routing Protocol) exhibits a notable efficiency in routing. It employs a clustering algorithm that divides the network into energy-based zones, forming quadrangle-shaped clusters. Nodes are uniformly deployed based on their energy levels within these zones. Energy factors influence probability and threshold values for cluster head election. QBCR boasts the longest network lifetime, along with the highest stability period and average energy consumption per round. Authors in [17] present a hierarchical routing protocol utilizing two levels of energy heterogeneity for WSNs, dividing the network into two zones based on node energy. In the Improved Zonal Stable Election Protocol (IZ-SEP), normal nodes communicate directly with the BS, while advanced nodes employ clustering techniques. This strategy aims to extend network lifetime by minimizing energy consumption. CHs are chosen based on residual energy and the number of neighbors within the cluster range, prioritizing nodes with higher residual energy and more neighbors for efficient energy usage. In [14], an energy-efficient hierarchical routing protocol for WSNs, called Threshold-based Energy-aware Zonal Efficiency Measuring (TEZEM) hierarchical routing protocol, is proposed. TEZEM aims to optimize network efficiency by enhancing the CH selection process through zone-based network division. It ensures equitable CH distribution in each round, promoting effectiveness and efficiency. Performance evaluation and simulation results confirm that TEZEM significantly enhances network lifetime, throughput, and stability.

In [16], a novel technique has been developed to reduce energy consumption and increase network lifetime in three-level energy HWSNs. Three regions—super nodes, advanced nodes, and standard nodes—make up the sensing area. In order to improve CH selection, thresholds are specified during setup to choose nodes with higher residual energy. In high-density locations, the number of CHs is regulated via a node state transformation mechanism. The approach chooses the most energy-efficient path for data transport. Although this method increases the lifetime of the network, it does not solve problems like data loss or the hotspot issue in multi-hop transmissions. Authors in [20] proposed the Stable Zones Protocol for Heterogeneous Wireless Sensor Networks (SZP-H). SZP-H is based on partitioning the WSN area into two zones. Each region varies in dimensions, the number of nodes, the level of initial energy of the nodes, and the distance from the BS. Additionally, they provide a formula to calculate the amount of energy that should be added to a zone based on its distance from the BS. This ensures that each zone maintains the same throughput without affecting the overall lifetime of the WSN.

In summary, routing protocols for WSNs consider the initial energy levels of nodes, distinguishing between homogeneous and heterogeneous nodes. They also account for area partitioning into multiple zones and the division of nodes into clusters. The communication styles include single-hop and multi-hop types, with communication occurring between nodes or between nodes and the BS. Our focus is on developing the Z-MSP for a zonal network area with homogeneous nodes, utilizing single-hop communication, both within and between zones.

III. SYSTEM MODEL

The fundamental system model in this study encompasses both the network model and the energy model.

A. The Network Model

The division of a WSN's area into multiple zones is driven by application requirements and is also considered a means of enhancing the WSNs' lifetime. Therefore, we aimed to determine the optimal division of the area, which led to the optimal number of clusters, set at 10 as utilized in the LEACH protocol. We randomly deployed 100 nodes across an area measuring 100 m × 100 m. However, the use of zones required us to allocate the same area to each zone, ensuring an equal number of nodes in each. Additionally, to implement Z-MSP, we assigned a fixed sink to each zone, responsible for transmitting the collected data to the central base station.

B. The Energy Model

The standard LEACH energy model [7] provides a representation of the main operations of a WSN. Because LEACH is a clustering-based protocol, it models the transmission, reception, and aggregation operations as given in (1)-(3). However, (1) is divided into two equations related to the parameter d_0, as given by (4).

$$E_{Tx} = \begin{cases} L.E_{elec} + L.\epsilon_{fs}.d^2 & if\ d < d_0 \\ L.E_{elec} + L.\epsilon_{mp}.d^4 & if\ d \geq d_0 \end{cases} \quad (1)$$

$$E_{Rx} = L.E_{elec} \quad (2)$$

$$E_{DA} = L.E_a \quad (3)$$

E_{Tx}, E_{Rx}, and E_{DA} represent the energy consumed during the steps of data transmission, reception, and aggregation, respectively. E_{Tx} is defined by (1) to achieve a better Signal-to-Noise Ratio (SNR) and minimize energy consumption during data transmission. The parameters involved are: L: the data length in bits, E_{elec}: the energy consumed in transmitting one bit of data, and E_a: the energy consumed in aggregating one bit of data. d_0 is the threshold distance value used to determine which of the two equations should be applied in the calculations.

$$d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}} \quad (4)$$

where ϵ_{fs} represents the transmitter amplifier in the energy-free space model and ϵ_{mp} represents the transmitter amplifier in the energy multipath model.

IV. Z-MSP PROTOCOL CHARACTERISTICS STUDY

To properly define or characterize a protocol for a WSN, particularly one focused on energy enhancement, it is essential to consider several factors. First, we must address the type of nodes involved, distinguishing between homogeneous and heterogeneous nodes based on their initial energy levels. Additionally, we need to account for the characteristics of the area being monitored and the type of routing algorithm employed, whether it is clustering-based or not. Our Z-MSP protocol is designed for homogeneous WSNs and operates on a zonal basis. It is implemented across 100 nodes distributed within a 100 m × 100 m area. The Z-MSP network comprises 100 nodes evenly distributed across 10 zones, each covering the same area, as illustrated in Figure 1. Within each zone, there are 10 nodes deployed over a 100 m² area. However, the zones do not have identical dimensions. This prompted us to seek a balanced dimensionality with an equal number of zones along both the x and y axes. For instance, dividing both axes by three results in nine zones does not facilitate achieving an equitable distribution of nodes across the same area space. Therefore, our aim was to achieve uniform areas with an equal number of nodes (i.e., 10) per zone, a goal accomplished through the area partitioning depicted in Figure 1.

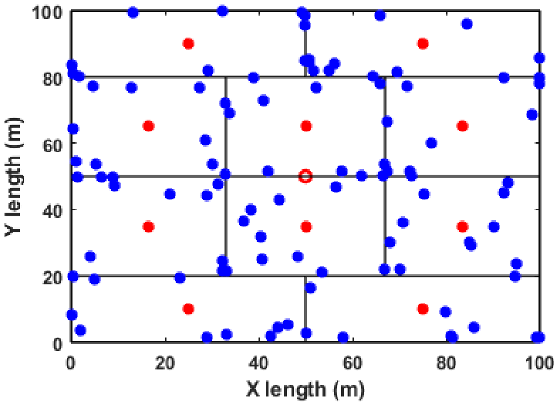

Fig. 1. Z-MSP's simulated WSN topology.

A. The Proposed Protocol

In this section we present the pseudocode of the proposed Z-MSP algorithm (Algorithm 1). Z-MSP operates as an MSP for each zone. The MSP determines the sending rate based on the energy consumed by a node to transmit its packets to its sink, divided by the energy required to send a packet over the shortest distance in the WSN. This ensures synchronized data transmission among nodes. Consequently, the application continues to function until the nodes' energy is completely depleted, leading to simultaneous node failure (see the simulation results section).

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ALGORITHM 1: Z-MSP protocol deployment and operation
BEGIN
1. Deploy nodes randomly in different zones, 10 nodes per zone.
2. Assign each zone a fixed sink node.
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3. BS.broadCast("start message");
4. for all sink nodes do
   sink.broadCast("start message");
end for
5. for all node(i) do
   node(i).getDistToSink(RSSI);
   node(i).sendToSink("ok to start",
node(i).dToSink);
end for
6. ZHs.selectMinDist;
7. ZHs.broadCast(minDist);
8. for all node(i) do
   node(i).sendingRate =
enrTx(node(i).dToSink) / enrTx(minDist);
   node(i).sendingRateVar =
node(i).sendingRate;
end for
9. 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
```

V. SIMULATION RESULTS

To assess the performance of the proposed Z-MSP, we conducted a comparative analysis against well-known protocols in the field, namely FBECS, E-CAFL, and LEACH-FC, all of which are recent and widely recognized. The evaluation involved testing these protocols in various aspects. FDN, MDN, and LDN represent the First Dead Node, Middle Dead Node, and the Last Dead Node, respectively.

- Lifetime: This refers to the duration of network operation until the demise of the first node (FDN).
- Throughput: This measures the number of packets transmitted during the simulation until the last node's expiration.

We used MATLAB R2024b online version for the simulations. The network topology utilized in our experiments is depicted in Figure 1. The network consists of 100 nodes, distinguished by a blue color, each initialized with an energy level of 0.5 J. Additionally, there are 10 sinks strategically placed to gather data from nodes within their respective zones. Subsequently, these sinks transmit the collected data to the BS, depicted by a red circle positioned at the center of a 100 m × 100 m area.

Table I presents the details of the network zone topology. The dots defining the regions are arranged in a counterclockwise fashion. Table II resumes the simulation parameters.

TABLE I. THE WSN SIMULATED TOPOLOGY DETAIL

Zone	Dots	Sink Coordinates	No. of nodes
01	(0, 80), (50, 80), (50, 100), (0, 100)	(25, 90)	10
02	(50, 80), (100, 80), (100, 100), (50, 100)	(75, 90)	10
03	(0, 50), (33, 50), (33, 80), (0, 80)	(16.5, 65)	10
04	(33, 50), (67, 50), (67, 80), (33, 80)	(50, 65)	10
05	(67, 50), (100, 50), (100, 80), (67, 80)	(83.5, 65)	10
06	(0, 20), (33, 20), (33, 50), (0, 50)	(16.5, 35)	10
07	(33, 20), (67, 20), (67, 50), (33, 50)	(50, 35)	10
08	(67, 20), (100, 20), (100, 50), (67, 50)	(83.5, 35)	10
09	(0, 0), (50, 0), (50, 20), (0, 20)	(25, 10)	10
10	(50, 0), (100, 0), (100, 20), (50, 20)	(75, 10)	10

TABLE II. SIMULATION PARAMETERS

Parameter	Value
Network area	100 m × 100 m
Number of nodes	100
Node initial energy	0.5 J
Number of rounds	5000

Figure 2 illustrates the lifespan of Z-MSP compared to its predecessors. The simulation results demonstrate that Z-MSP has successfully stabilized the WSN for the longest duration.

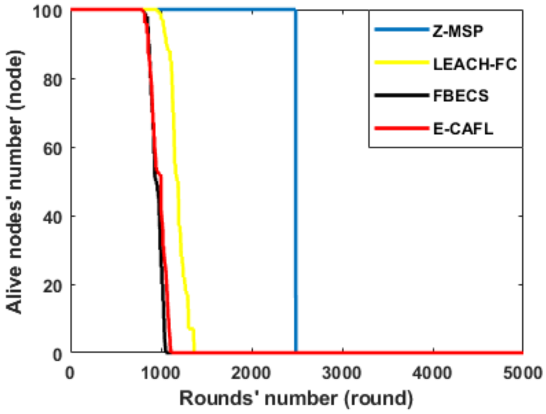

Fig. 2. Protocol lifetime period.

Table III summarizes the percentage enhancements in Z-MSP WSN's stable period compared to FBECS, E-CAFL, and LEACH-FC. According to Table III, Z-MSP increased the stable period by 211.5%, 211.5%, and 183.5% compared to FBECS, E-CAFL, and LEACH-FC, respectively.

TABLE III. LIFETIME IMPROVEMENT OF Z-MSP COMPARED TO FBECS, E-CAFL, AND LEACH-FC.

Protocol	**Lifetime (rounds)**	**Z-MSP's enhancement percentage**
Z-MSP	2492	/
FBECS	800	211.5 %
E-CAFL	800	211.5 %
LEACH-FC	879	183.5 %

Figure 3 illustrates the packet transmission counts by Z-MSP, FBECS, E-CAFL, and LEACH-FC over the simulation period. It is evident that Z-MSP outperforms the other protocols in terms of throughput. Z-MSP has successfully preserved all MSP results across various performance parameters.

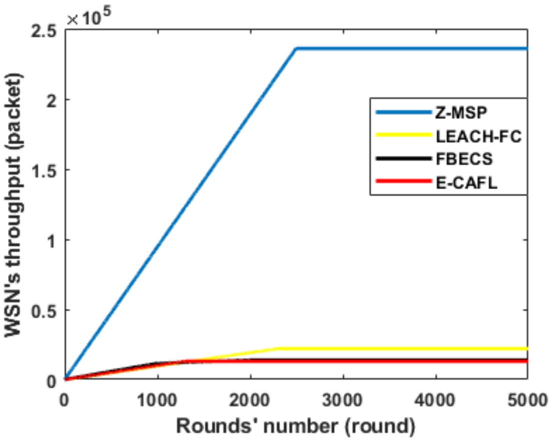

Fig. 3. Throughput vs number of rounds.

VI. CONCLUSION

Zonal-WSNs represent a partial solution to energy conservation in WSNs. To enhance the MSP protocol, which effectively maximizes the performance of WSNs, we introduced the Z-MSP protocol based on a zonal architecture. The zonal partitioning designs a WSN as a set of zones, each of which operates independently. The objective is to develop an MSP version tailored for this specific architecture. Our Z-MSP is composed of 10 zones, which is the optimal number according to the LEACH protocol for clusters. To demonstrate that the proposed Z-MSP achieves the same level of efficiency for Z-WSNs as MSP does for homogeneous WSNs, we compared Z-MSP to FBECS, E-CAFL, and LEACH-FC. Z-MSP surpassed them in various routing protocol performance metrics such as lifetime, throughput, FDN, MDN, and LDN. It improves the network's stable period by 211.5%, 211.5%, and 183.5% compared to FBECS, E-CAFL, and LEACH-FC, respectively. Additionally, it achieves the highest values for throughput, FDN, MDN, and LDN.

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