Received: February 18, 2023. Revised: May 27, 2023.

International Journal of
Intelligent Engineering & Systems

http://www.inass.org/

Energy-Efficient Mobile Data Ferry Pathway Construction Protocol Based on Transmission Coverage and Hybrid Differential Search Algorithm in Wireless Sensor Networks

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Abstract: Energy efficiency and energy hole phenomena are still dominant issues in wireless sensor networks. Based on recent studies, mobile data ferry could be a powerful approach to address these vital issues. Determination of sojourn points and efficient pathway design is vital in this approach. However, mobile data ferry visits to specific nodes make a long tour distance. Moreover, improper sojourn points affect to energy consumption. This paper proposes an energy-efficient mobile data ferry pathway construction protocol (EEMDFPC) based on transmission coverage and a hybrid differential search algorithm (DSA). EEMDFPC establishes non-overlapping clusters and selects the optimal CHs by adopting hybrid DSA. Hybrid DSA is an improvement of DSA by employing particle swarm optimization (PSO) and chaotic map. Moreover, the proposed protocol discovers the sojourn points based on the full coverage area and the intersection area between CHs in a minimum number. Next, hybrid DSA with swap strategic constructs mobile data ferries route. Performance evaluation of the proposed protocol was carried out in a simulated environment and compared with the MSEAC-4R and MSEAC-8R protocols. The evaluation results show that the proposed protocol can extend the network lifetime compared to MSEAC-4R, MSEAC-8R, and LEACH_CD are 15.08%-25.63%, 7.72%-17.76%, and 10.41%-29.44% respectively. The proposed protocol can also prolong the stability compared to MSEAC-4R and MSEAC-8R, namely 643-1025, 621-965 rounds, and 18-546 rounds, respectively. The superior performance of the proposed protocol proves that the proposed protocol operates efficiently and reduces the energy hole problem.

Keywords: Wireless sensor network, Energy efficient, Mobile data ferry, Transmission coverage, Differential search algorithm.

1. Introduction

Innovation in the field of wireless sensor network (WSN) technology shows an increasing trend. This technological progress is also driven by the rapid development of other technologies such as microelectronic, sensors, and wireless [1]. WSN is built by connecting many small devices, namely sensor nodes, using wireless communication media. The sensor node is responsible for observing objects or phenomena in an environment. Then the sensor node sends the observed data to the base station (BS) or the sink [2]. Data retrieval and transmission require sensor nodes to operate relatively long [3, 4]. Although sensor nodes have limitations in size, computation, storage capacity, energy, and communication, sensor nodes take on heavy-duty [5].

Meanwhile, WSN is widely applied to environmental observations that are hostile and expansive scale, such as the military, battlefields, volcanoes, natural disasters, radiation exposure, and structured health monitoring [6]. The harsh environmental conditions make it difficult for humans to access to recharge or replace batteries because the sensor nodes only use the battery as the energy source.

Network lifetime is still the main focus of research at WSN [7, 8]. The majority of energy is spent on the communication process, especially during data transmission [9]. Thus, sensor nodes far from the sink need to transmit data by multi-hop. Multi-hop data transmission strategy can reduce energy consumption. However, the multi-hop method has an impact on sensor nodes adjacent to the sink. Sensor nodes near the sink consume energy quickly because of the massive energy consumption [10]. At a particular time, sensor nodes far from the sink still have 93% residual energy from the initial energy, sensor nodes near the sink have no energy [10, 11]. When the sensor nodes near the sink are off, the sensor nodes far from the sink are difficult to transmit [12]. The network between the sensor node and the sink can be disconnected [13]. This phenomenon is called the energy hole problem.

In addition to multi-hop, a clustering method is proposed to reduce transmission distance and data redundancy. The low-energy adaptive clustering hierarchy (LEACH) was the first protocol to initiate the cluster approach [14]. To date, the LEACH protocol is still prominent [15–17]. In the cluster strategy, the sensor nodes are divided into several groups. Furthermore, the sensor nodes are grouped into two categories, namely: cluster member (CM) and cluster head (CH). The cluster method offers low overhead, low traffic density, preventing data redundancy, and energy efficiency [18, 19]. However, CH bears a more significant burden than CM. Thus, the unbalanced load distribution can shorten the network lifetime.

Another strategy to consider is sink or node mobilization. The concept of the mobile sink was introduced in research [20, 21]. In this concept, the sink is not static. Apart from mobile sinks, a mobile data ferry scheme was proposed in the study [22]. In the mobile data ferry strategy, one or more special nodes move to the regular nodes to collect data from the regular sensor nodes and carry the data to the sink. The existence of a data ferry can overcome the communication limitations of regular nodes in separate areas. Low congestion, energy efficiency, network stability, and the ability to solve energy hole challenges are the advantages of data ferries. However, this strategy has challenges, namely the sojourn points and movement patterns. The sensor nodes will consume excessive energy if sojourn points are not precise. Another impact is that the mobile data ferry needs to travel long distances to collect data.

The sojourn point can be determined using a cluster strategy such as studies in [9, 13, 23]. In this strategy combination, the data ferry stops at every CH. Meanwhile, the study in [24] proposed the midpoint of the entire CH as a sojourn point. However, the number of clusters or grids that are fixed and not optimal triggers CH to consume more energy when the network area gets wider. CH load distribution that is not considered can also shorten the network lifetime. Apart from determining the sojourn point, forming a mobile data ferry pathway is a non-deterministic polynomial-time hard (NP-hard) problem [25, 26].

Solving (NP-hard) problems requires a metaheuristic algorithm to obtain optimal results. Many metaheuristic algorithms have been used to find optimal results globally in WSN [27]. The differential search (DS) algorithm is a relatively new metaheuristic algorithm proposed by Civicioglu [28]. The behaviour of swarms of migrating living organisms is the main idea of the DS algorithm. In many studies, the DS algorithm has shown good performance [29]. However, the DS algorithm also has weaknesses: slow convergence and sensitivity to random number generation [30].

This research proposes an energy-efficient mobile data ferry pathway construction protocol (EEMDFPC) based on transmission coverage and a hybrid differential search algorithm in wireless sensor networks. The proposed protocol aims to overcome the energy hole problem while saving energy consumption by utilizing mobile data ferries. The contribution of this research includes: (1). Utilization of hybrid DSA to form non-overlapping clusters and choose the optimal CH. Hybrid DSA combines PSO and a chaotic map. (2). The strategy for searching sojourn points is based on the full coverage area and the intersection area between CHs in a minimum number to ensure one-hop communication. (3). Hybrid DSA with swap operator and swap sequence to form an efficient mobile data ferry route.

The rest of this paper is organized as follows. Section 2 discusses the research related to this study. The energy and network model are described in section 3. Section 4 provides a detailed description of the proposed protocol. Section 5 describes the simulation to evaluate the performance of the protocol and discuss the results. Finally, the conclusion is listed in section 6.

2. Related works

In 2020, Chauhan and Soni proposed a mobile sink movement protocol based on the energy efficiency cluster method (MSEAC) [24]. MSEAC consists of two, MSEAC-4R and MSEAC-8R. In MSEAC-4R, the grid area is divided into four grids. Meanwhile, MSEAC-8R divides the network area into eight grids. In each grid, the firefly metaheuristic algorithm looks for sensor nodes eligible to be CH. After that, the midpoint of all CH is set as the sojourn point. CH communication to the mobile sink can be single-hop or multi-hop. This protocol excels at mobile sink travel times. However, a fixed number of grids and uneven load distribution can increase energy consumption. Especially when the network area increases.

Sahoo, Amgoth, and Pandey [31] proposed a CH selection protocol and mobile sink movement using the particle swarm optimization (PSO) algorithm. This protocol is named PSO-based energy efficient clustering and sink mobility (PSO-ECM). PSO-ECM determines the eligibility of sensor nodes to become CH based on energy consumption rate (ECR), distance, energy, average energy, and node degree. After selecting CH and forming clusters, the next process is to determine the movement of mobile sinks. The movement pattern of the mobile sink is, of course, influenced by where the mobile sink stops to collect data from the CH. In PSO-ECM, mobile sink sojourn locations are selected based on the lowest residual CH energy. Other factors to be considered in the movement of mobile sinks are the distance of the CH from the sink and cluster size. PSO-ECM produces advantages in terms of stability period, network lifetime, half-node dead, and throughput. However, multi-hop communication used by CH that is far from the mobile sink sojourn location can cause high delays.

Pamungkas, Djanali, and Anggoro [26] proposed the development of a mobile sink protocol based on a combination of differential search (DSA) algorithms and PEGASIS, abbreviated as MSDSP. MSDSP utilizes DSA to select optimal mobile sink stopover locations in each sub-region. After the sojourn locations in each sub-region have been determined, MSDSP selects a node as a chain leader (CL) by employing DSA. Parameters of residual energy estimation and CL distance to the mobile sink sojourn location determine the feasibility of the sensor node becoming CL. The chain formation process then follows the selection of CL in each sub-region by utilizing the PEGASIS protocol. MSDSP focuses on reducing the CL burden because CL does not need aggregating data from sensor nodes in the same sub-region. However, DSA has the potential to be stuck at the local optimum so that it can result in suboptimal mobile sink sojourn location.

Wang, Gao, Liu, Sangaiah, and Kim proposed a routing algorithm that improves energy efficiency with mobile sink [32]. This algorithm divides the network area into sectors. The CH selection stage follows this sector-forming stage in each sector. The residual energy and the distance from the sensor node to the sink are considered whether the node can be CH. After each sector has a CH, a greedy algorithm is adopted to link one CH to another in the form of a topological chain. The CH closest to the sink is selected as the chain leader. In this routing method, the mobile sink moves in a circle in a counter clockwise direction. However, when CH dies unexpectedly, communication to the sink becomes disconnected and fails.

Gupta and Saha [33] proposed a protocol for forming load-balanced clusters and determining mobile sink points to collect data from CH. This proposed protocol utilizes artificial bee colony and differential evolution algorithms to form clusters and select CH by considering load balance. There are three parameters used to designate a sensor node to become a CH, namely the distance between the CH and all cluster members, the residual energy of the CH, and the delay time. Furthermore, the artificial bee colony algorithm is tasked with finding mobile sink sojourn points as close as possible to all CHs. This protocol can generate a short mobile sink route. However, the CH transmission energy will increase when the node density is low, and the WSN area is vast.

Hung, Thi Noc, The, Ngoc, Huynh, and Dien Tam [34] developed the LEACH centralized (LEACH-C) protocol coupled with a mobile sink approach or LEACH_CD for short. The idea of this proposed protocol is based on the assumption that the mobile sink approach can reduce energy consumption. LEACH-C is used to select CH based on residual energy and build clusters because LEACH-C can build clusters more efficiently than LEACH. Next, Dijkstra's algorithm determines the direction of movement of the mobile sink from sink to each CH. The simulation results show the superiority of LEACH_CD compared to LEACH and LEACH-C. However, mobile sink stops at each CH can result in long routes when the network area is large. In addition, LEACH_CD focuses only on residual energy to regulate CH selection.

Sayeed and Shree [35] proposed a data collection protocol with an unmanned aerial vehicle (UAV). This data collection protocol makes the UAV a mobile sink. Before the sojourn points are determined, the network area is divided by a multilevel clustering algorithm approach. Thus, a cluster can consist of one or more sub-clusters. Each sub-cluster has a CH. The sensor node that acts as the CH is also a sojourn point for the UAV. The ant colony algorithm was utilized to form the optimal route for the UAV. This protocol allows the UAV to stop at many points, which can cause high delays in the case of a large number of nodes. In addition, selecting a CH that ignores the energy factor can trigger a communication failure to the UAV because the CH can turn off suddenly.

Singh, Amin, and Choudhary [36] proposed a method for controlling sink movements based on a

Table 1. Definition of symbols in section 3

Symbols	Meaning
$E_{Tx}(ns_i, ns_j)$	Energy required by the sensor node ns_i to transmit β bit data to the sensor node ns_j.
E_1	Energy consumed by transmitter circuit.
E_2	Energy spent by amplifier component.
E_2	Energy consumed by receiver component.
$\delta(ns_i, ns_j)$	Transmission distance from sensor node ns_i to sensor node ns_j.
ε	Exponent to express the path loss model
E_{fs}	The required energy by amplifier component to transmit 1 bit data in free space propagation model.
E_{mp}	The consumed energy by amplifier component to transmit 1 bit data in multi-path propagation model.
δ_{th}	Threshold transmission distance.
$E_{Rx}(ns_j, \beta)$	The required energy by the sensor node ns_j to receive β bit data.
β	Message length in bit.

genetic algorithm. The proposed method consists of three phases. The first phase is network initialization. In this phase, the genetic algorithm looks for sink locations in each cluster. The clusters built in the network area are square and have the same number of nodes. After the proposed protocol has finished determining the optimal CH locations in each cluster, the second phase is to carry out real-time CH selection. Three parameters are considered in the selection of CH: the remaining energy of the node, the distance of the node to the optimal CH location, and the number of nodes in the selection of CH in the previous round. Then in the last phase, the mobile sink moves to the optimal CH locations in each cluster to collect data from the CH. Determination of the optimal CH location is the focus of the proposed protocol. However, the optimal mobile sink movement schedule and the route have yet to be considered.

3. System model

First, we provide a brief description of the network model developed for this proposed protocol. Next, we will also describe the energy model used in this study.

Algorithm 1 EEMDFPC protocol

Input: Number of sensor nodes n, network area $X_{na} \times Y_{na}$, a set of sensor nodes NS, energy E, location of sink, speed of mobile data ferry v_{mdf}, and location of mobile data ferry $locMDF$.

Output: Cluster formation, a set of CH, a set of sojourn points. and trajectory of mobile data ferry.

```
Initialize all network parameters
Sink broadcasts message in initial stage
while the number of functioning sensor nodes $n_{fn} > 0$ do
    Compute mean distance to the departure point of mobile data ferry $\delta_{todp}$
    Compute the optimum number of clusters $nc_{opt}$
    Build cluster topology
    Sink broadcasts Cluster-Id and the position of virtual CH
    while $nc_{opt} > 0$ do
        Perform CH selection
        Add the selected sensor node to list of CH: $CHList \leftarrow ns_f$
        $numCH \longleftarrow numCH + 1$
        Set limits on the number of rounds to join in the CH elections
        CH broadcasts advertisement message and TDMA schedule to CM
        $nc_{opt} \leftarrow nc_{opt} - 1$
    end while
    Determine sojourn points
    Find the best path and construct trajectory of mobile data ferry
    Data gathering stage
    The sensor nodes update the energy level and send it to sink
    Sink updates the number of functioning sensor nodes $n_{fn}$
end while
```

3.1 Network model

The network model consists of three elements in the proposed protocol: sink, data ferry model, and sensor nodes. The sink position is static. In contrast, the mobile data ferry moves to collect data from the sensor node at a constant speed of v m/s. The departure point and return point of the mobile data ferry is the center of the network area. Sink and mobile data ferries have a significant source of energy.

We consider a set of sensor nodes $\mathcal{NS} = \{ns_1, ns_2, ns_3, .., ns_n\}$ distributed over the network area randomly. The position of the sensor nodes is static after being deployed in the network area. Sensor nodes also know their respective positions. All sensor nodes have the same capabilities for computing, sensing, and communicating. The size of storage capacity and energy is the same for each sensor node. The non-rechargeable battery is used as an energy source. So, if the battery runs out, the sensor node will not operate for the next round. The communication channel is symmetrical, so each node's energy expended to transmit a message is the same.

3.2 Energy model

Assume a sensor node $\mathcal{ns}_i$ transmits a message of size β bits to sensor node $\mathcal{ns}_j$ with transmission distance $\delta(\mathcal{ns}_i, \mathcal{ns}_j)$. Thus, the energy required by $\mathcal{ns}_i$ to send the message can be calculated by the following formula [14]:

$$E_{Tx}(\mathcal{ns}_i, \mathcal{ns}_j) = \beta\left(E_1 + E_2[\delta(\mathcal{ns}_i, \mathcal{ns}_j)]^{\varepsilon}\right) \quad (1)$$

In this formula, E_1 and E_2 respectively represent the energy of the transmitter and amplifier components to transmit one bit of data and ε is the exponent of the path loss model whose value is 2 or 4. The value of E_2 and ε depends on whether the transmission distance is less than or exceeds the threshold distance δ_{th}. In the case, the transmission distance is less than the distance threshold, then the path loss model chosen is free space propagation, and the values of E_2 and ε are 10 pJ/bit/m^2 and 2. On the other hand, the path loss mode selected is path fading propagation, and the values of E_2 and ε are 0.0013 pJ/bit/m^4 and 4, respectively. E_{fs} symbolize E_2 for the free space propagation model, and E_{mp} represents E_2 for multi-path propagation model. The formula for calculating the distance threshold is as follows:

$$\delta_{th} = \sqrt{\frac{E_{fs}}{E_{mp}}} \quad (2)$$

Meanwhile, the sensor node $\mathcal{ns}_j$ as the recipient of the message also expends energy which can be calculated based on the following formula:

$$E_{Rx}(\mathcal{ns}_j, \beta) = \beta E_3, \quad (3)$$

where E_3 is the energy consumed by the receiver component to receive 1 bit of data. Table 1 shows the details of the symbols in section 3.

4. Proposed protocol.

In protocols based on data ferry movement, sojourn point, and the length of the path traversed by the mobile data ferry substantially impact energy efficiency and QoS. Thus, to support energy efficiency and QoS efforts, the path length should be as minimal as possible. Also, the sojourn point should be close to the mobile data ferry. However, finding short mobile data ferry paths becomes a complex challenge. The number of the sojourn points for the mobile data ferry affects the distance travelled by the mobile data ferry. The main idea of this proposed protocol is to minimize the number of sojourn locations and find strategic sojourn points.

Round expresses the operating time in the proposed protocol. In each round, the proposed protocol operates in four phases: a cluster formation phase, a CH selection phase, a sojourn point search phase, a mobile data ferry pathway construction phase and a data collection phase. The hybrid DS algorithm is utilized in the cluster formation phase, CH selection, and mobile data ferry pathway construction.

4.1 Cluster formation

In cluster-based protocols, the optimal number of clusters also significantly affects the level of energy efficiency and network lifetime. Calculation of the optimal number of clusters refers to the study [8]. At the beginning of each round, the proposed protocol calculates the optimal number of clusters in the network area. Next, clusters are formed in the network area with an optimal number. The formation process in the proposed protocol is also referred to in the study [8]. Since cluster formation is an Np-hard problem, the proposed protocol builds clusters utilizing a hybrid differential search algorithm (HDSA). This HDSA combines the DS algorithm with particle swarm optimization (PSO) and chaotic maps to produce a cluster topology that can minimize energy use.

4.2 CH selection and rotation mechanism

CH selection is the next stage after all living sensor nodes are divided into several clusters. This stage takes place in each cluster. The sensor node responsible as CH has an extra burden compared to the cluster members. Thus, several factors need to be considered to reduce excessive energy use and ensure that the CH does not die suddenly.

In the proposed protocol, the factors that are considered to determine a sensor node worthy of being a CH adopt research in [8] with adjustments.

The first factor is the residual energy after the node performs the task as CH (E_{er-ns}). In general, other protocols only pay attention to the current residual energy. This consideration allows CH to run out of energy and die suddenly. Meanwhile, the estimation of residual energy after becoming a CH can ensure that the sensor node still has the energy to carry out its functions in the next round. The second factor is the proximity of candidate CH to virtual CH (δ_{vch-ns}). The closer the transmission distance from the candidate CH to the virtual CH can minimize the energy requirements of the sensor node to transmit data to the CH. Thus, cluster members also have enough energy to become CH in the next round. The last factor is the distance of the CH candidate to the mobile data ferry departure point (δ_{dp-ns}). This factor is a consideration so that the mobile data ferry distance can be minimized. The three factors that form the basis for evaluating the feasibility of the sensor node being selected as CH are as follows:

$$Minimize\ F_{CH} = \delta_{dp-ns} + \delta_{vch-ns} - E_{er-ns} \quad (4)$$

In the protocol proposed in this study, HDSA calculates the feasibility of the sensor nodes in the cluster to be CH by referring to Eq. 4. The sensor node will be selected as CH if the sensor node has a minimum value. Furthermore, the sensor node selected as CH in a cluster sends a CH_ADV message to other sensor nodes in the same cluster. This message sent by CH contains the CH_ID. The final step in selecting CH is determining the number of rounds for the new CH to participate in CH selection again. Thus, the other sensor nodes also have the chance to become CH in the next round. In addition, the stability period becomes long. The rotation mechanism in [8] becomes a reference in the proposed protocol.

4.3 Sojourn point discovery

In this phase, the proposed protocol looks for strategic sojourn points for mobile data ferries. Selecting a strategic mobile data ferry sojourn point can result in energy efficiency and good data transmission success rates. The mobile data ferry can collect data from more than one CH in the strategic sojourn point. Also, the CH can communicate directly with the mobile data ferry in one hop.

Based on these criteria, the area that has the potential to become a sojourn point for the mobile data ferry is the area where the nodes are in full communication coverage and the area where the communication signal slices between CHs. The proposed protocol focuses on finding sojourn points in these two areas in this study.

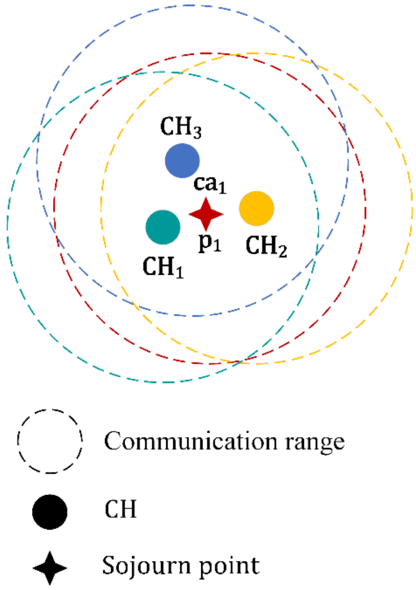

Figure. 1 Full communication coverage of CH

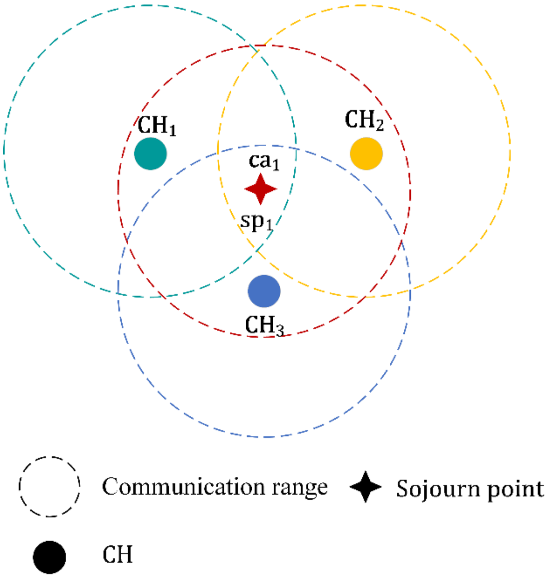

Figure. 2 Partial communication coverage of CH

Figs. 1 and 2 illustrate areas that benefit energy consumption, namely ca_1. If the mobile data ferry stops at a certain point, namely sp_1 and collects data from the CH around that point, then the CH can communicate with the mobile data ferry in just one hop. In addition, the stop at sp_1 can save visiting time. Thus, delay can be minimized even though the network area is increasing. However, the challenge is the mechanism for determining the sp_1 stopover point.

The search mechanism for sojourn points in the proposed protocol is shown in algorithm 2. In the initial stage of searching for sojourn points, each CH_i calculates the distance to CH_j. The results of this calculation are then compared to whether CH_j is within the full communication range or the partial communication range with CH_i. In this study, a communication range ($RComm$) of node sensor is set to 50 m. Two considerations form the basis for determining the distance of this communication range, namely (1). at a distance of up to 50 meters, the data transmission success rate is 100% [37]; (2). efficient transmission energy consumption rate [38]. If the neighbouring CH_j falls within the full communication range, then CH_i includes it in the set FCH_i. In the case the communication CH_i intersects with the communication signal CH_j, then CH_i has it in the set PCH_i.

After each CH knows its position relative to another CH, it needs to determine whether it has positional dualism or not. A CH can only choose CH in full or partial communication coverage. This selection is essential to ensure that the CH only sends data to the mobile data ferry when the mobile data ferry stops at a certain point. If the CH has two different positions, the mobile data ferry will move in an inefficient trajectory pattern. Therefore, the CH, which is in full communication coverage and intersects with several other CHs, chooses based on the highest number. If the CH has more intersections than the full communication coverage, then the CH joins other intersecting CHs. Instead, the CH will join another CH in full communication coverage.

Furthermore, the stopover points are traced to the complete communication coverage and intersection areas. In the whole communication coverage area, if the farthest CH location and the nearest CH location to the mobile data ferry departure point are $(x_{CH}^{max}, y_{CH}^{max})$ and $(x_{CH}^{min}, y_{CH}^{min})$ respectively, then the stopover point for the mobile data ferry can be formulated as follows:

$$sp_i = \left(\frac{x_{CH}^{max}+x_{CH}^{min}}{2}, \frac{y_{CH}^{max}+y_{CH}^{min}}{2}\right) \qquad (5)$$

In contrast to the entire communication range, the search for stopover points in the area where the communication coverage is intersected is influenced by the intersection points of the communication range of each CH. So, the intersection location of the communication range must be obtained in advance to get the right stopover point for the mobile data ferry. In the case of two CHs which communication ranges intersect, the stopover point for the mobile data ferry is the midpoint of the line connecting the two intersection points ip_1 and ip_2, with the following formula:

$$sp_i = \left(\frac{1}{2}\sum_{k=1}^{2} x_{ip_k}, \frac{1}{2}\sum_{k=1}^{2} y_{ip_k}\right) \qquad (6)$$

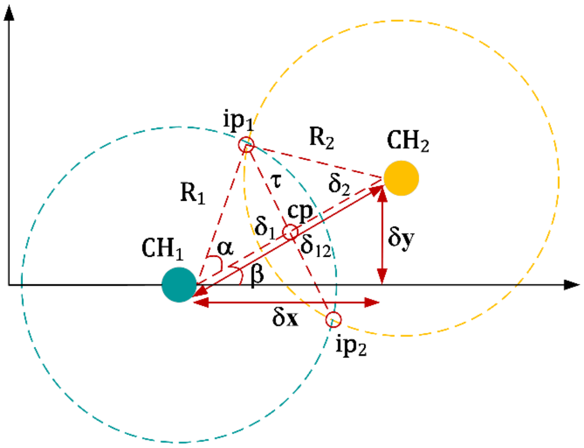

Figure. 3 Intersection points of two CHs

where (x_{ip_k}, y_{ip_k}) is intersection point ip_1 and ip_2.

Assume that (x_{CH_1}, y_{CH_1}) and (x_{CH_2}, y_{CH_2}) are positions CH_1 and CH_2, respectively, the distance between the two CH is δ_{12}, and the two intersecting CH communication signals have a range of R_1 and R_2; we adopt the following formula to determine the position of the intersection point of the two signals:

$$\begin{aligned} x_{ip_{1,2}} &= x_{CH_1} + R_1 \cos(\beta \pm \alpha) \\ y_{ip_{1,2}} &= y_{CH_1} + R_1 \sin(\beta \pm \alpha) \end{aligned} \qquad (7)$$

According to the law of cosines, the angle α on Eq. 7 can be calculated by the following:

$$\alpha = \cos^{-1}\left(-\left(\frac{R_2^2-R_1^2-\delta_{12}^2}{2R_1\delta_{12}}\right)\right) \qquad (8)$$

While the angle β can be found using the following formula:

$$\beta = \tan^{-1}\left(\frac{y_{CH_2}-y_{CH_1}}{x_{CH_2}-x_{CH_1}}\right) \qquad (9)$$

4.4 Mobile data ferry pathway construction

In each round, the mobile data ferry must travel from the departure point to each sojourn point exactly once and end at the starting point again. The distance travelled by the mobile data ferry must be as minimal as possible. The search for the pathway with the shortest distance to collect data is like the travelling salesman problem (TSP). It is an NP-hard problem whose solution requires a metaheuristic approach. In the proposed protocol, HDSA finds that the total tour distance of mobile data ferry is no longer than the maximum total tour distance (TD_{max}). Here is the formula to calculate the maximum total tour distance:

$$TD_{max} = 2(X_{na} + Y_{na}) + \sqrt{X_{na}^2 + Y_{na}^2} \quad (10)$$

where X_{na} and Y_{na} indicate the network area size.

This mobile data ferry pathway can be defined as a directed graph $G = (V, E)$, where V is the set of vertex that represents the sojourn points in the network area and E is the set of directed endpoints or arcs. Each pair of endpoints $(i, j) \in E$ has a value which is the distance between the arrival point i and the arrival point j where $i, j \in V$. Assume the mobile data ferry has a constant speed v_{mdf}, minimizing the distance from mobile data ferry departure point to the first sojourn point (SP_{dp,sp_1}), the distance between sojourn point ($SP_{sp_i,sp_{i+1}}$). Distance between last sojourn point to departure point ($SP_{sp_n,dp}$), the mobile data ferry travel time can be formulated as follows:

$$TT = \frac{\min\limits_{sp \in SP}\left\{SP_{dp,sp_1} + \sum_{i=1}^{n-1} SP_{sp_i,sp_{i+1}} + SP_{sp_n,dp}\right\}}{v_{mdf}} \quad (11)$$

4.5 Data-gathering

After the cluster formation phase, CH selection, stopover point search, and mobile data ferry trajectory construction are completed, each sensor node senses the environment's objects or phenomena. Furthermore, each cluster member transmits the scanned data to its CH. Data transmission to the CH is carried out based on the TDMA schedule shared by the CH to each cluster member. Each cluster member gets a time slot to send data to the CH in this scheduling mechanism. When a sensor node gets time to transmit data, the sensor node can take advantage of the available bandwidth. Then, the sensor node goes into sleep mode after sending data to the CH. There are two advantages of TDMA scheduling, namely, avoiding data packet collisions and extending the network lifespan [39].

CH performs data processing once data is received. Like sending data from cluster members to CH, sending data from CH to mobile data ferry also refers to the TDMA schedule. Thus, when the mobile data ferry stops at one point, each CH sends data to the mobile data ferry according to the specified time allocation. The mobile data ferry moves to the next stopover point at a constant speed according to the itinerary that has been built. The exact process is repeated until all stopover points in the network area are visited, and data is collected from all CHs. After the mobile data ferry completes its task, it returns to the starting point.

4.6 Hybrid differential search algorithm in WSN

The differential search algorithm (DSA) is a relatively new metaheuristic algorithm proposed by Civicioglu [28]. The pattern of migration carried out by living organisms is the basic idea of DSA. The migration of living things is a unique natural phenomenon. Many living organisms such as dolphins, whales, birds, fire ants, butterflies, bats exhibit periodic migratory behaviour, which is generally triggered by seasonal changes.

Seasonal changes significantly impact the survival of living organisms, especially in terms of the availability of food sources and generation continuity. Thus, living organisms migrate from their original habitat to a new habitat that allows living organisms to survive and reproduce. In the process of searching for new habitats rich in food sources, the migration of living organisms shows a pattern that can be modelled as a Brownian-like random walk [40]. This movement model is adopted in DSA.

When living organisms decide to migrate, they form swarms referred to as superorganisms. On their way to a new habitat, superorganisms stop at a site that fulfils their needs for a certain period. However, if the superorganism finds a richer habitat in food sources, the superorganism will migrate to that new habitat.

In DSA, superorganism is population of artificial organisms that reflect random solutions to problems. This superorganism is expressed as:

$$Superorganism_g, g = \{1,2,3, \dots, G\} \quad (12)$$

where G is the maximum number of generations. While artificial organism that is member of superorganism is symbolized as:

$$AO_i, i = \{1,2,3, \dots, nPop\} \quad (13)$$

Here $nPop$ is the population size. Furthermore, each artificial organism consists of D members ($ao_{ij}, j = \{1,2,3, \dots, D\}$).

In standard DSA, the step after population initialization is to randomly select the artificial-organisms to go towards the targets of $donor = [AO_{random\_shuffling(i)}]$ for finding a stopover site. However, in HDSA, the proposed Particle Swarm Optimization (PSO) algorithm [41] searches for the best artificial organism to reach the target donor. Thus, the desired stopover can be shifted to the global minimum quickly. The following are the targets of donor at HDSA:

$$donor = AO_{donorPSO(i)} \tag{14}$$

The formula for finding a stopover site is:

$$Stopover = Superorganism + Scale \times (donor - Superorganism) \tag{15}$$

HDSA combines DSA with PSO and takes advantage of chaotic maps to improve DSA's performance in achieving global minimums. In standard DSA, there are ten random number generators [42]. However, the random number generator $rand_8$ is replaced with chaotic maps.

Algorithm 3 Utilization of chaotic maps in HDSA

```
if chaoticMap(t) < p1
    map = rand(nPop,D)
    for i1=1: nPop do
        map(i1,:) = map(i1,:) < $rand_9$
    end for
Else
    map = ones(nPop,D)
    for i2=1: nPop do
        map(i2,randi(D)) = map(i2,randi(D)) < $rand_{10}$
    end for
end if
```

Here chaoticMap(t) indicates the value of chaotic map in *t-th* iteration.

4.7 Design efficient pathway based on HDSA

Every metaheuristic algorithm has specific characteristics. Thus, adjustments to the metaheuristic algorithm need to be made to provide the best results from a problem. PSO and DSA are examples of many metaheuristic algorithms developed to solve continuous problem [28, 43]. Meanwhile, the TSP solution is a discrete approach. Therefore, the PSO and DSA standards are not suitable for solving problems from a TSP point of view.

HDSA adopted a swap operator and swap sequence [43] to design and construct a mobile data ferry line in the proposed agreement. These ideas are utilized in PSO and DSA to produce a minimum global solution.

In the ide swap operator, the normal solution order of nodes is $SX = \{sx_1, sx_2, \ldots, sx_{numn}, sx_1\}$ with $numn$ nodes and having the node-set $V = \{1,2,\ldots,numn\}$ where $sx_i \in V$ and $sx_i \neq sx_j, \forall i \neq j$, then the swap operator $SwOp(i,j)$ can be defined as the exchange of node sx_i and node sx_j in the SX solution series. Furthermore, $newSX = SX \Diamond SwOp(i,j)$ is defined as the new solution series after the operation $SwOp(i,j)$ on SX. The symbol $\Diamond$ represents the binary-swap operation.

Swap sequence is defined as the set of different swap operators in a certain order. Assume $SwSeq = (SwOp_1, SwOp_2, \cdots, SwOp_{numn})$ where $SwOp_1, SwOp_2, \cdots, SwOp_{numn}$ are swap operators. The swap sequence can act on a solution. If the swap sequence applies to a solution, then all the swap operators in the swap sequence act on the solution in the sequence. This rule can be described in the following equation:

$$newSX = SX \Diamond \mathrm{SwSeq} = \mathrm{SX} \Diamond (SwOp_1, SwOp_2, \cdots, SwOp_{numn}) \tag{16}$$

5. Performance assessment and results analysis

5.1 Performance assessment

We conducted a series of experiments to measure the performance of the proposed protocol under certain conditions. Experiments were carried out through simulation under the MATLAB environment. The parameters used in this simulation are shown in detail in Table 2. Especially for the parameters related to the energy model, the parameter values refer to the study in [14]. Moreover, simulation was performed until all sensor nodes died.

In this experiment, two hundred sensor nodes were spread over a network area measuring 50 m × 50 m, 100 m × 100 m, and 200 m × 200 m. The variation of network area with a fixed number of nodes in this experiment is intended to evaluate the scalability of the proposed protocol. Mobile sink based energy-aware clustering (MSEAC) [24] and LEACH_CD [34] were used to compare the performance of EEMDFPC. MSEAC is divided into two, namely the MSEAC-4R and MSEAC-8R protocols. In the MSEAC-4R protocol, the network area is divided into four regions. Meanwhile, the MSEAC-8R protocol divides the network area into eight regions. The regional numbers on MSEAC-4R and MSEAC-8R are fixed.

The parameters used to assess the performance of the proposed protocol are as follows:

- Network lifetime is the interval of time required since the sensor nodes start operating until all sensor nodes in the network area die due to running out of energy.

Table 2. The details of simulation parameters

Simulation parameters	Value
Number of nodes	200
WSN Area	50 m × 50 m, 100 m × 100 m, 200 m × 200 m
E_{ec}	50 nJ/bit
E_{fs}	10 pJ/bit/m^2
E_{mpf}	0.0013 pJ/bit/m^4
E_{da}	5 nJ/bit
E_0	0.5 J
Packet's size	4000 bits

- The first node dies (FND) is the number of rounds when one sensor node in the network area fails for the first time.
- Half of the nodes die (HND) is the number of rounds when half of the nodes deployed in the network fail.
- The last node dies (LND) is the number of rounds when all nodes in the network area fail.
- The stability period is the time interval from when all nodes start operating until FND.
- The period of instability is the period from FND to LND.
- Total energy consumption is the amount of energy consumed by all sensor nodes in one round.
- Average residual energy is availability energy at each sensor node in one round.

5.2 Results analysis

In this study, the emphasis is on the ability of the EEMDFPC protocol to operate over a long period. In addition, the performance of the proposed protocol to perform in the stability period is highlighted in this study. The experimental results are presented in Table 3 and Figs. 4-12.

Table 3 shows the results of testing the performance of the EEMDFPC protocol in terms of network lifetime. The ability of the protocol to work over a long period can be assessed from three parameters, namely FND, HND, and LND. This experiment is intended to evaluate the effect of increasing the size of the network area on the network lifetime. This evaluation is essential because WSN is built on a large area, so that the proposed protocol must be able to adapt to the size of the network area. Based on the data listed in Table 4, the EEMDFPC protocol has the highest FND value for the three network area sizes. The FND values of the EEMDFPC protocol are 1135 rounds, 1131 rounds, and 993 rounds, respectively. Meanwhile, the MSEAC-4R protocol has the lowest FND values of 110 rounds, 210 rounds, and 359 rounds, respectively. The FND values of the MSEAC-8R protocol are also relatively low, namely 170 rounds, 531 rounds, and 372 rounds, respectively. Likewise, the FND values of LEACH_CD are 1117, 1070, and 447, respectively. Thus, EEMDFPC can extend the stability period for the three different network areas. Balanced load distribution to all sensor nodes is the key for EEMDPFPC to produce relatively high FND.

In the LND parameter, the EEMDFPC protocol excels for network area sizes of 100 m × 100 m and 200 m × 200 m. In experiment with a network area measuring 50 m × 50 m, the MSEAC-8R protocol produced the highest LND value, 1415 rounds. However, in a network area measuring 100 m × 100 m, EEMDPFPC extended LND compared to MSEAC-4R, MSEAC-8R, and LEACH_CD, which were 15.08%, 7.72%, and 16.34%. For a network area of 200 m × 200 m, EEMDPFPC also increased LND compared to MSEAC-4R, MSEAC-8R, and LEACH_CD by 25.63%, 17.76%, and 29.44%. The increase in the LND value on the EEMDPFPC indicates that EEMDPFPC can prolong the network lifetime.

Figs. 4, 5, and 6 show the changes in the number of live nodes for the EEMDFPC, MSEAC-4R, MSEAC-8R, and LEACH_CD protocols in the 50 m × 50 m, 100 m × 100, and 200 m × 200 m network areas. The MSEAC-4R and MSEAC-8R protocols seem to have relatively short network stability, then the number of nodes continues to decrease slowly. Meanwhile, the EEMDFPC protocol can maintain network stability relatively long. After a long period of stability has passed, the nodes enter a period of instability. During this period of instability, the cluster structure changes frequently. This change in cluster structure affects the allocation of node rotation to follow the selection of CH. Thus, the number of live nodes in the EEMDFPC protocol decreases gradually and transmission distance increases. Therefore, a rotation mechanism that is adaptive to the dynamics of the cluster structure is needed to keep the nodes operating in the long term.

The discussion of network lifetime in WSN has a strong relationship with the level of energy consumption per round and the average residual energy of each node per round. Figs. 7, 8, and 9 show the level of energy consumption of each protocol in each round at different network area sizes, namely 50 m × 50 m, 100 m × 100, and 200 m × 200 m. Along with the increase in the network area, the EEMDFPC protocol produces the lowest level of energy consumption compared to MSEAC-4R, MSEAC-8R, and LEACH_CD protocols. These results indicate

Received: February 18, 2023. Revised: May 27, 2023.

Table 3. Network lifetime with varying network area size

Protocols	Network Lifetime								
	50 m × 50 m			100 m × 100 m			200 m × 200 m		
	FND	HND	LND	FND	HND	LND	FND	HND	LND
EEMPFPC	**1135**	1236	1378	**1131**	**1217**	**1381**	**993**	**1146**	**1240**
MSEAC-4R	110	1243	1360	210	1152	1200	359	919	987
MSEAC-8R	170	1216	**1415**	531	1163	1282	372	1008	1053
LEACH-CD	1117	1197	1248	1070	1136	1187	447	817	958

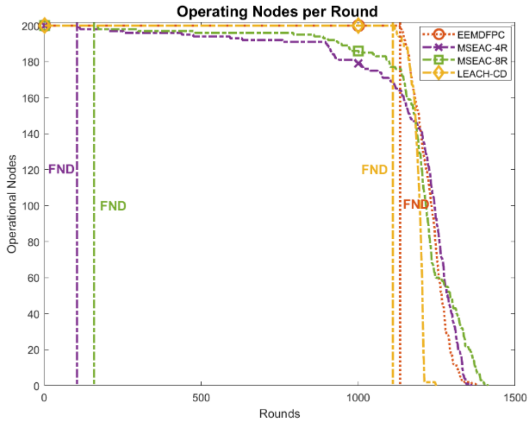

Figure. 4 Operating nodes per round with the network area size 50 m × 50 m

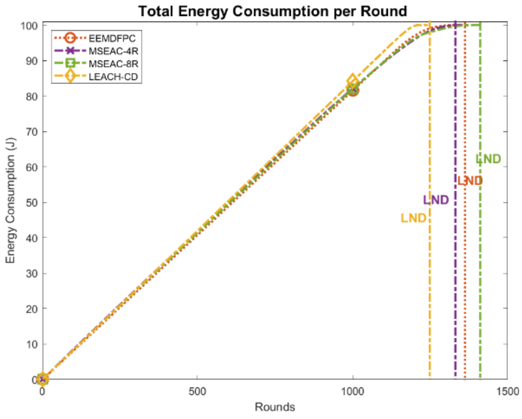

Figure. 7 Total energy consumption per round with the network area size 50 m × 50 m

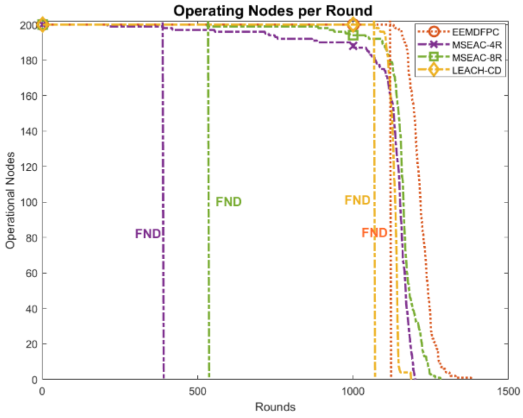

Figure. 5 Operating nodes per round with the network area size 100 m × 100 m

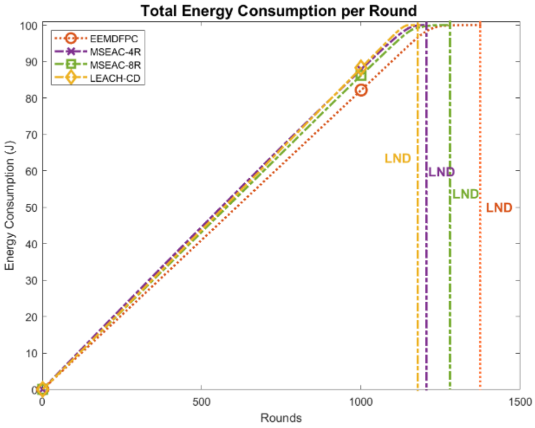

Figure. 8 Total energy consumption per round with the network area size 100 m × 100 m

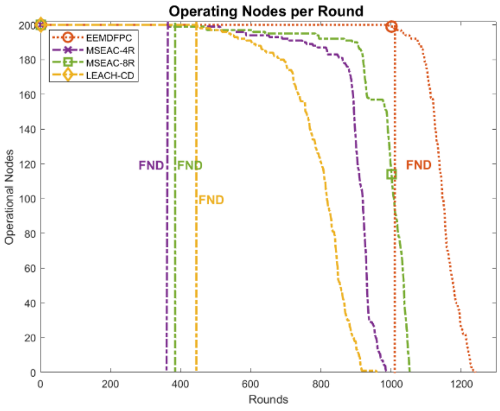

Figure. 6 Operating nodes per round with the network area size 200 m × 200 m

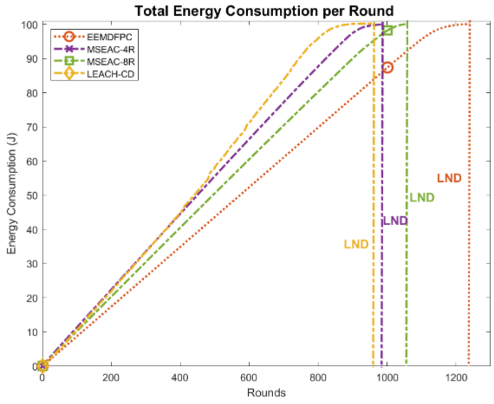

Figure. 9 Total energy consumption per round with the network area size 200 m × 200 m

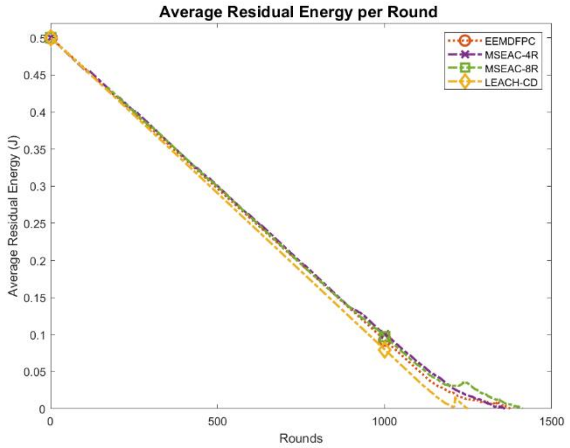

Figure. 10 Average residual energy per round with the network area size 50 m × 50 m

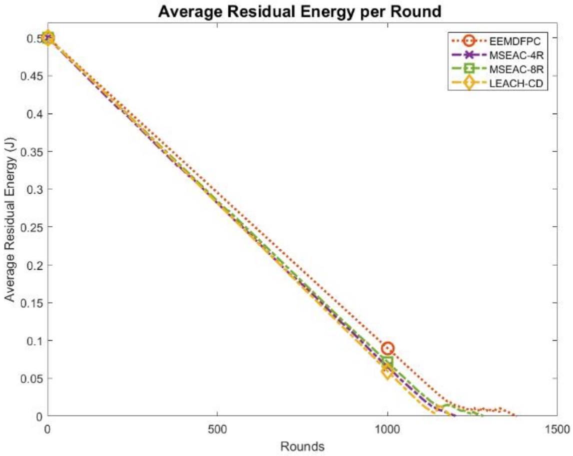

Figure. 11 Average residual energy per round with the network area size 100 m × 100 m

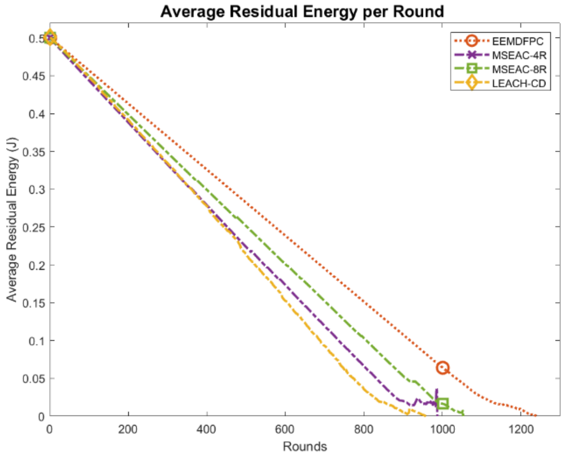

Figure. 12 Average residual energy per round with the network area size 200 m × 200 m

that the EEMDFPC protocol is adaptive to increasing network area and can maintain energy efficiency. The single-hop mode of communication and the determination of sojourn points contribute to the advantages of the EEMDFPC. Meanwhile, the MSEAC-4R and MSEAC-8R protocols expend more energy as the network area increases. The increase in transmission distance and multi-hop between CH causes an increase in energy consumption on the MSEAC-4R and MSEAC-8R.

In addition, the average residual energy node per round is used to provide an overview of the energy efficiency of each protocol. The average residual energy per round for the three different tissue areas is shown in Figs. 10, 11, and 12. As for the total energy consumption, the average residual energy of EEMDFPC is higher than MSEAC-4R, and MSEAC-8R for network areas measuring 100 m × 100 m, and 200 m × 200 m. In the network area, 50 m × 50 m, the average residual energy of EEMDFPC dropped to lower than that of MSEAC-8R since FND. This decrease is caused by nodes far from the departure point of the mobile data ferry being selected as CH. Thus, the sojourn point for the mobile data ferry is around the network area boundary. However, the average residual energy of EEMDFPC is higher than LEACH_CD.

6. Conclusion

An energy-efficient mobile data ferry pathway construction (EEMDFPC) protocol based on transmission coverage and hybrid differential search algorithm is proposed in this article. The EEMDFPC protocol establishes strategic sojourn points for mobile data ferries to stop. Thus, the CH around the sojourn point only needs one hop to communicate with the mobile data ferry. Furthermore, EEMDFPC designs and builds a mobile data ferry pathway that fulfils the minimum travel distance. Strategic sojourn points and minimal mobile data ferry distance are, of course, also supported by cluster stability, the optimal number of CH, and even load distribution.

Based on experimental results through a series of simulations, the EEMDFPC protocol can improve energy efficiency, network lifetime, stability period, scalability, and reduce energy hole problems compared to the MSEAC-4R, MSEAC-8R, and LEACH_CD protocols. In terms of network lifetime, EEMDFPC can operate longer than MSEAC-4R , MSEAC-8R, and LEACH_CD which are 15.08%-25.63%, 7.72%-17.76%, and 10.41%-29.44%, respectively. EEMMDFPC also produced a more extended stability period than MSEAC-4R, MSEAC-8R, and LEACH_CD are 643-1025 rounds and 621-965 rounds, and 18-546 rounds respectively.

Conflicts of interest

We declare that there is no conflict of interest regarding publishing this article.

Author contributions

Conceptualization, KNP. Pamungkas, S. Djanali, and R. Anggoro; methodology, KNP. Pamungkas; software, KNP. Pamungkas; formal analysis, KNP. Pamungkas; writing—original draft preparation, KNP. Pamungkas; writing—review and editing, S. Djanali and R. Anggoro; supervision, S. Djanali and R. Anggoro.

Acknowledgments

This research was made possible with the support and assistance of Institut Teknologi Sepuluh Nopember and Politeknik Negeri Banjarmasin.

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