



An optimization of distributed Voronoi-based collaboration for energy-efficient geographic routing in wireless sensor networks

M. Sridhar¹ · P. B. Pankajavalli¹

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Abstract

In energy-constrained wireless sensor networks (WSNs), geographic routing (GR) also known as location-aware routing has been developed because it uses neighbourhood locality data as an alternative of overall topology information for routing. But, this protocol frequently suffers from the energy holes in the data transmission resulting in path failure. To avoid this problem, energy-aware dual-path GR (EDGR) protocol has been suggested to improve the routing path from energy holes. However, it is unable to heal the energy holes since the node mobility can generate new energy holes. Also, higher mobility distance can cause high energy consumption (EC) and node failure. Hence in this article, an energy-efficient distributed collaboration mechanism is proposed with EDGR for k -coverage energy holes detection and healing in WSN that minimizes the delivery delay (DD). In this protocol, the distributed Voronoi-based collaboration (DVOC) method is applied in which the nodes can cooperate in energy holes detection and recovery. The nodes are enabled to monitor each other node's critical locations around themselves by constructing the local Voronoi diagrams (LVDs). Moreover, an optimized DVOC (ODVOC) is proposed with EDGR in which intelligent water drop (IWD) algorithm is used to find the globally optimized routes to minimize the DD. Finally, the simulation outcomes demonstrate the ODVOC-EDGR accomplishes higher effectiveness than the EDGR and DVOC-EDGR in terms of different performance metrics.

Keywords WSN · Energy-aware geographic routing · Energy holes · Local voronoi diagram · Intelligent water drop algorithm

1 Introduction

Typically, WSNs are having more number of sensor nodes deployed in various applications like defense, agricultural activity monitoring, atmospheric conditions forecasting, healthcare systems, smart vehicles, and home automation. Once the nodes are deployed, each sensor node must have the capability to autonomously organize them into a wireless communication network. Also, they have the ability to accumulate and process the data as well as transmit the sensed data to one or more sink nodes via wireless link in multihop transmission manner. In these

networks, each sensor node is equipped with the restricted power resources which are not easy to restore. In general, these types of networks are classified with denser levels of node's functionality, unpredictability, constrained power, computation, and storage. These sole features and restrictions may cause several problems [1]. Specifically, the routing holes or energy holes have occurred i.e., a region free of nodes nearer to the destination is barely circumvented in WSNs in different authentic geographical atmospheres like blockage, constructions, etc. This acquires more EC for data transmission. Therefore, those networks require an appropriate energy-aware GR protocol to implement various network control techniques such as node localization, synchronization and network prediction with reduced EC and increased Network Lifetime (NL).

Typically, a routing protocol is a process to select a suitable path for transmitting the data from one node to another. In previous years, different energy-aware GR protocols have been suggested to improve data

✉ M. Sridhar
srimanoharan6@gmail.com
P. B. Pankajavalli
pankajavalli.g@gmail.com

¹ Department of Computer Science, Bharathiar University, Coimbatore, India

transmission. GR has been developed for resource-constrained WSNs because it utilizes neighborhood position data obtained by Global Positioning System (GPS) receiver rather than overall topology data for packets transmission. Their protocols do not need allocation of routing tables for all sensors. So, these protocols are having high efficiency and scalability for WSNs [2, 3].

Most of the protocols are easy to be executed, but the most familiar limitation is that they perform only one region of the energy holes for recovering the path. Such protocols can provide the traffic load congregated on the edge of the energy holes and degrade the network efficiency in data transmission. Also, all these protocols do not ensure data transmission in an energy-efficient way. Distributed Voronoi based Cooperation scheme (DVOC) uses the Local Voronoi Diagrams which helps in the avoidance of hole. Nodes in the network govern only their transmission path and DVOC made constraint for every node. Based on the constraint, generation of new holes in the critical path is avoided. Huang et al. [4] proposed an EDGR protocol to achieve enhanced path recovery from energy holes. This protocol uses local data, remaining power and the features of EC to decide the routing path. Also, two node-disjoint anchor lists sent via two regions of the energy holes were used for altering the route to achieving load-balancing. Besides, this protocol was extended to 3D sensor networks for achieving an energy-aware routing that deviates energy holes. On the other hand, the node mobility can create fresh holes when moving to recover the existing ones and longer moving space can cause other nodes to terminate since their energy is exhausted i.e., the nodes are not able to identify the energy holes. Also, it does not have the ability to heal the energy holes.

The delivery of data to the destination is interrupted by various factors such as energy holes, traffic and exhaust of energy. Among this energy holes place vital role in the interruption of data delivery. As a result, this article focuses on detecting and healing energy holes efficiently by avoiding the new holes generation. The delayed delivery that is caused due to energy hole is rectified with the effective design of protocol that detects and prevents the energy holes. In this protocol, an energy-efficient distributed collaboration method is proposed for k -coverage energy holes discovery and recovery in WSN with EDGR protocol that reduces the DD. Also, the DVOC method is proposed where the nodes collaborate in detecting and healing the energy holes. It facilitates the nodes to observe the other's key points around themselves by constructing the LVDs. After that, it constrains the movement of each node for avoiding the generation of fresh holes. If a node does not arrive at its destination because of the constraint, its holes recovery process will transfer to the other collaborating nodes i.e., k th generating node. Moreover, this

protocol is further improved as ODVOC-EDGR to reduce the moving space of the nodes based on the IWD algorithm that minimizes the total amount of moving routes i.e., obtain the globally optimized paths that reduce the DD significantly. Thus, the energy holes generated in the network is detected and healed to minimize the DD significantly.

The rest of the article is structured as follows: Section II presents the earlier investigations of the energy-efficient GR protocols for WSN. Section III describes the methodology of DVOC-EDGR and ODVOC-EDGR in detail. Section IV demonstrates the simulation results for DVOC-EDGR and ODVOC-EDGR. Section V concludes the research work and suggests future scope.

2 Literature survey

Chen et al. [5] proposed an Adaptive Position Update (APU) scheme for GR that fine-tunes the frequency of PU using the mobility dynamics of the nodes and the transmission models [6]. This strategy was performed based on two rules such as nodes whose mobility were harder to predict update their locations regularly and nodes nearer to forwarding paths restore their locations frequently. However, load-balancing was not achieved and the optimal transmission range was needed to improve the protocol performance. Cheng et al. [7] proposed an Efficient QoS-aware Geographic Opportunistic Routing (EQGOR) protocol for achieving QoS including end-to-end consistency and delay constraints in WSNs. In this protocol, a forwarding candidate set was efficiently selected and prioritized. However, average link quality per-hop was not effective.

Petrioli et al. [8] presented an Adaptive Load-Balancing Algorithm with Rainbow (ALBA-R) protocol for WSN in which the cross-layer mixture of GR with contention-based MAC was performed for selecting the relay and balancing the load. Also, another mechanism was used for detecting and routing around connectivity holes. However, end-to-end latency was high. Coutinho et al. [9] proposed the Geographic and opportunistic routing with Depth Adjustment-based topology rule for transmission Recovery (GEDAR) protocol over invalid regions [10]. In this protocol, the local data of the neighboring nodes and few well-known sonobuoys were used for selecting the next-hop forwarder group of neighbors to maintain data transmission. Also, an invalid node healing depth regulation based topology rule algorithm was proposed to shift invalid nodes to fresh depths for restarting the GR. However, Packet Delivery Ratio (PDR) was less and NL was not considered.

Hieu et al. [11] proposed a Stability-Aware GR protocol for secure data transmissions in Energy-Harvesting

(SAGREH) WSNs. By using this protocol, a reliable paths selection method was provided to increase the NL. Particularly, the influences of link quality on the network performance were analysed [12]. The link quality was computed based on the packet reception rate of all routes between the source and sink node. After that, the most reliable route was chosen for transmitting the packets. However, average hop count and EC were high.

Huang et al. [13] proposed an Energy-efficient Multicast GR (EMGR) that constructs an energy-aware multicast tree based on the energy for directing multicast data transmission and adaptively selecting the nodes nearest to the power-optimal relay position as the subsequent transmission [14]. Moreover, the RTS/CTS beaconless handshaking method was employed for constructing the local planarized Relative Neighborhood Graph (RNG) that removes a redundant cost for multicast GR [15]. However, control overhead was high while the network density was increased. Increase in control overhead may lead the poor performance and the delay in delivery of data.

Adnan et al. [16] suggested a Secure Region-Based GR (SRBGR) protocol for increasing the chance of choosing the suitable relay node. In this protocol, additional authorized nodes can be considered for routing by extending the allocated sextant and applying various message contention priorities [17]. Moreover, the bound set window was used for an adequate gathering interval and authentication rate for intruder detection and mitigation. However, the impact of more number of nodes as needed to analyze with different scenarios of network configurations.

3 System model

In this part, the DVOC-EDGR and ODVOC-EDGR are explained in brief. Consider that all sensor nodes have its position information and are dense enough for enabling the

whole network to the well linked. Also, consider that sensor nodes can literally travel in any direction in the target area and there is no obstacle region where sensor nodes cannot travel in. Assume a group of sensor nodes $S = \{1, \dots, N\}$ disseminated over a target region Λ where the location of node u is characterized by its Cartesian coordinate (x_u, y_u) .

3.1 Distributed Voronoi-based collaboration with EDGR (DVOC-EDGR) protocol

Initially, k -order VD is constructed by DVOC and k -coverage checking is performed based on the LVD. Typically, LVD assigns the node u nearest to a critical location of node v for conducting the precision analysis and k -coverage analysis on this location. Therefore, LVD minimizes the ring where the u requests to gather the position data. Thus, GPS searching space and the number of probed nodes of all nodes are minimized. In addition, a redundant searching cost due to the overlapping is avoided.

Observe that u 's 1-order Voronoi cell is equally restricted to any 1-order Voronoi cell of other node's position. After that, LVD is defined as the intersection of u 's 1-order Voronoi cell and k -order VD. After that, the local k -order VD of each sensor node should be equally restricted. As well, the grouping of LVD creates the whole k -order VD. The set of locations that node u has gathered is denoted as \mathcal{L}_u . Subsequently, the local k -order VD of u is described as the intersection of u 's 1-order Voronoi cell and the k -order VD of \mathcal{L}_u :

$$\widehat{V}_k^u(\mathcal{L}_u) \triangleq V_k(\mathcal{L}_u) \cap \mathcal{V}_1(u) \quad (1)$$

In Eq. (1), $V_k(\mathcal{L}_u)$ is the k -order VD given by \mathcal{L}_u . An LVD $\widehat{V}_k^u(\mathcal{L}_u)$ is said to as accurate if $\widehat{V}_k^u(\mathcal{L}_u) = \widehat{V}_k^u(\mathcal{L}_u)$.

Algorithm 1 for LVD Construction:

Input: $\mathcal{L}_u = \{u\}$ //Initially, node u only has its own position;

Output \hat{V}_k^u ;

1. **while**(precision = TRUE)
2. Precision \leftarrow TRUE; //Represent whether the LVD is precise
3. Compute \hat{V}_k^u based on the current \mathcal{L}_u using Eq. (1);
4. **for**(each $v \in \hat{V}_k^u$) do
5. Discover a k^{th} generating node of v i.e., node v ;
6. Utilize GPS for searching the closest node to v in S/\mathcal{L}_u i.e., node x ;
7. **if**(node x is nearer to v than node v)
8. Put node x to \mathcal{L}_u ;
9. Precision=FALSE;
10. End **if**
11. End **for**
12. End **while**

In DVOC, once the sensor nodes construct their own k -order LVDs, they cooperate with each other for detecting whether the vertices of the cells in the diagram i.e., critical locations are k -ordered by discovering if each vertex is covered by its k th generating node. Normally, a sensor node travels towards the Voronoi vertex that is uncovered. Nonetheless, such node mobility may cause few regions to become discovered and much iteration may be required for converging while a fresh energy hole cannot be discovered by few other nodes. Hence, a technique is proposed for enabling a node to detect its secure region that it must not travel out. If the node travels out of the secure region, it no longer discovers its critical location.

If \square is a vertex of a k -order Voronoi cell, then \square should be the intersection of the bisectors $\mathcal{B}_{u,v}$ and the k th generating nodes of \square are u, v and x . Based on this, for any vertex \square of a k -order Voronoi cell, \square has at least three k th generating nodes i.e., u, v and x , and \square denotes the centroid of the ring of $\Delta_{u,v,x}$. Besides, in the circle of $\Delta_{u,v,x}$, there should be $(k - 1)$ nodes closer to the centroid of ring than the triangle's three vertices which indicate that the ring should have accurately $(k - 1)$ nodes. Thus, $(k - 1)$ order Delaunay Triangle (DT) is obtained by linking the three k th generating nodes of any critical location in a node's LVD.

Algorithm 2 for Energy Holes Detection by Node u :

Input: \hat{V}_k^u ;

Output: $[C_{hole}^k, G_{hole}]$ // C_{hole} is the group of critical locations undiscovered, G_{hole} is the group of C_{hole}^k 's generating nodes;

1. **for**(each critical location v in \hat{V}_k^u)
2. Discover v 's k^{th} generating nodes G_v ;
3. **for**(each node $v \in G$)
4. **if**(node v cannot cover v)
5. Put v to C_{hole} ;
6. Put node v to G_{hole} ;
7. End **if**
8. End **for**
9. End **for**

If the k th generating a node's sensing distance discovers their critical location, then the radius of their $(k - 1)$ -order DT is lesser than or identical to their sensing distance. So, the issue that whether the radius of each of such $(k - 1)$ -order DTs less than the sensing distances of the k th generating nodes. The correlation among the radius of triangle's bounded ring (r) and triangle's three edges ($e_{u,v}, e_{u,x}, e_{v,x}$) for making the three k th generating nodes to discover their critical location i.e.,

$$r = \frac{e_{u,v}e_{u,x}e_{v,x}}{\sqrt{(e_{u,v}^2 + e_{v,x}^2 + e_{u,x}^2)^2 - 2(e_{u,v}^4 + e_{v,x}^4 + e_{u,x}^4)}} \quad (2)$$

According to Eq. (2), any vertex of a k -order Voronoi cell can be discovered by its k th generating nodes if the correlation of its $(k - 1)$ -order DT's three edges guarantee the following criterion:

$$R_S \geq \frac{e_{u,v}e_{u,x}e_{v,x}}{\sqrt{(e_{u,v}^2 + e_{v,x}^2 + e_{u,x}^2)^2 - 2(e_{u,v}^4 + e_{v,x}^4 + e_{u,x}^4)}} \quad (3)$$

Assume a $(k - 1)$ -order DT $\Delta_{u,v,x}$ where u and v are not moving, the secure region of x for $\Delta_{u,v,x}$ refers to the region where x can be placed to ensure that the triangle's circumcenter is k -covered. According to this, node x 's secure region for $\Delta_{u,v,x}$ is computed. According to the Eq. (3), the position of x must ensure one of the following conditions where $(i_x, j_x), (i_u, j_u)$ and (i_v, j_v) denote the Cartesian coordinates of x, u , and j correspondingly.

$$(i_x - i' + f_i)^2 + (j_x - j' + f_j)^2 \leq R_S \quad (4)$$

$$(i_x - i' - f_i)^2 + (j_x - j' - f_j)^2 \leq R_S \quad (5)$$

where $i' = \frac{i_u + i_v}{2}, j' = \frac{j_u + j_v}{2}, f_i = |i_v - i_u| \sqrt{(R_S/e_{u,v})^2 - \frac{1}{4}}$ and

$$f_j = |j_v - j_u| \sqrt{(R_S/e_{u,v})^2 - \frac{1}{4}} \times \frac{i_u - i_v}{j_v - j_u} \quad (6)$$

When x requires to travel to discover an energy hole, it must not travel out of its secure region of the other discovered critical location i.e., its position (i_x, j_x) must satisfy Eq. (4) and (5). Thus, the node's mobility is constrained by a secure region for preventing new energy holes from being generated [18]. After that, a collaboration scheme is also introduced to heal k -coverage energy holes when avoiding new energy holes being generated during node mobility. Consider, $S_m \subseteq S$ is the set of nodes that can travel where the nodes in S_m are called as mobile nodes. Mainly, S_m aims to exist in its secure region while traveling to discover its critical location. If it cannot travel to its destination, it requests another mobile generating node of a similar critical location to travel towards the energy hole for compensation.

While a node identifies that there exists a critical location v beyond the sensing range of its k th generating nodes, it will transmit a notification to all the three generating nodes. If there be at least one mobile generating node, then the mobile generating node is needed to travel towards v to recover the energy hole. If not, v requests to transmit the notification to a near mobile node that is further away from

v than v to renovate the k -coverage energy hole. Consider u is the mobile node that needs to travel to recover the k -coverage energy hole. After that, u discovers its destination d to discover the energy hole where d denotes the closest location that u desires to travel to formulate its sensing range arrive at its undiscovered critical location. At this point, the shortest route is the line that links u and u 's undiscovered critical location.

For preventing the new energy holes generation, node u needs to compute the secure region O_{joint}^u for all of its critical locations. Once the secure region is computed, node u finds the distance it needs to travel towards d . Assume d'

is the intersection of the line and O_{joint}^u . If d' is inside O_{joint}^u , node u directly travels to it; or else, the destination is d' . A collaboration scheme is introduced to overcome the problem that the node may not be capable to arrive at the computed destination due to the limit of a secure region. In this scheme, while a node cannot travel adequate space to arrive at its critical location, its collaborators i.e., nodes in a similar critical location are needed to travel to heal the energy holes. The detailed process of movement carried out by each node is described in Algorithm 3.

Algorithm 3 for Cooperative Movement Scheme of node u

Input: $[C_{hole}, G_{hole}]$;

Output: p_u //Destination of node u ;

1. Initialize $t = 0$;
2. **while**($t \leq \text{Time To Live (TTL)}$)
3. **for**(each $v \in C_{hole}$)
4. Inform all three v 's k^{th} generating nodes that v are remote of their sensing range. If there is no mobile k^{th} generating nodes, inform the nodes that are far away from v than the k^{th} generating nodes;
5. End **for**
6. Subsequent to the final movement, eavesdrop for an instance and accumulate the initial message (MSG) it receives;
7. **if**($MSG_type = MOV$) //MSG_type: Message type, MOV: Require the node to move;
8. $P \leftarrow MSG_loc$ //loc: Location of the destination;
9. **if**($P \notin O_{joint}^u$)
10. $P' \leftarrow ReDes(O_{joint}^u, P)$ //ReDes redetermines the node's destination while node's real destination is remote the secure region;
11. Move to P' ;
12. $P'' \leftarrow ParDes(u, v, x)$ //ParDes redetermines the node's collaborator's destinations;
13. $newMSG_type \leftarrow HELP$ //HELP: Consider the node request help from other nodes;
14. $newMSG_loc \leftarrow P''$;
15. Transmit $newMSG$ to node v ;
16. End **if**
17. End **if**
18. **if**($MSG_type = HELP$)
19. **if**($MSG_loc \notin O_{joint}^u$)
20. $P'' \leftarrow ParDes(u, v, k)$;
21. $newMSG_type \leftarrow FORCE$ //FORCE: Force the node to travel to a given destination;
22. $newMSG_loc \leftarrow P''$;
23. Transmit $newMSG$ to node v ;
24. End **if**
25. End **if**
26. **if**($MSG_type = FORCE$)
27. Move to MSG_loc ;
28. End **if**
29. $t + +$;
30. End **while**

Moreover, the moving distance is shortening by using IWD algorithm for reducing the total moving routes i.e., globally optimized routes.

3.2 Optimized distributed Voronoi-based collaboration with EDGR (ODVOC-EDGR) protocol

Each sensor node often discovers optimal moving path based on the activities and responses that take place among water drops and the water drops with the riverbeds. At each iteration, each water drop floods with speed and collects a quantity of soil. According to this, the following crucial features are described:

- Every water drop collects a quantity of soil relative to its speed. Therefore, the higher the velocity of drops, the larger the quantity of soil it brings.
- Speed of water drops raises further on routes with low soil quantity than on those with more soil quantity.
- While a water drop has to choose a route, it selects the route containing the less quantity of soil.

Therefore, artificial water drop is defined with two proprieties as:

- *Soil(IWD)*: The quantity of soil passed by the IWD.
- *Vc(IWD)*: The speed of the IWD.

The amount of soil (messages while a node discovering an energy hole or moving to recover it) from source (*u*) to destination (*d*) is denoted as *MSG(u, d)*. The velocity of this *MSG* transmission via the route is represented as *V^{ud}*.

$$V(t + 1) = V(t) + \frac{a_d}{b_d + c_d(MSG_t(u, d))} \tag{7}$$

In Eq. (7), *V(t + 1)* is the updated speed of water drop at subsequent node *d*, *a_d*, *b_d* and *c_d* are constant parameters for shortening the moving distance. An observed utility *E_f*

Table 1 Simulation parameters

Parameters	Values
No. of sensor nodes	150
Simulation area	1000 × 1000 m ²
Routing protocol	Dynamic source routing (DSR)
Queue type	CMUPriQueue
Initial energy	100 J
Packet size	300 bits
MAC type	MAC/802.11
IDS propagation	1.58%
Simulation time	65 ms

Table 2 Comparison of PDR vs. network densities

Network densities	EDGR	DVOC-EDGR	ODVOC-EDGR
1	0.94	0.951	0.958
1.15	0.95	0.962	0.969
1.3	0.964	0.975	0.982
1.45	0.964	0.975	0.982
1.6	0.972	0.981	0.986

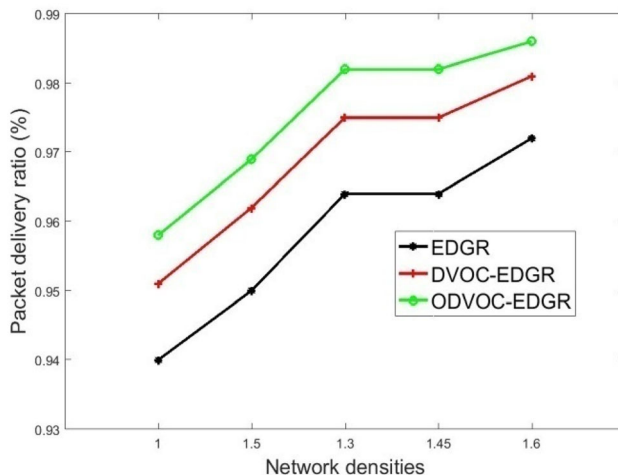


Fig. 1 PDR vs. network densities

is used to determine an undesirability of a water drop to travel from one node to another. The time (*time(u, d; V^{ud}(t + 1))*) taken by the water drop with speed *V^{ud}* to travel from *u* to *d* is computed as:

$$time(u, d; V) = \frac{E_f(u, d)}{\max(\varepsilon, V^{ud})} \tag{8}$$

In Eq. (8), the parameter ε is a positive value which is equal to 0.001. The function *E_f(u, d)* is the heuristic undesirability of moving a node from *u* to *d*. Regarding shorten the moving distance, *E_f(u, d)* is represented as *E_f^{op}*.

Table 3 Comparison of DD vs. network densities

Network densities	EDGR	DVOC-EDGR	ODVOC-EDGR
1	105	102	99
1.15	103	100	96
1.3	100	97	93
1.45	97	94	90
1.6	94	91	87

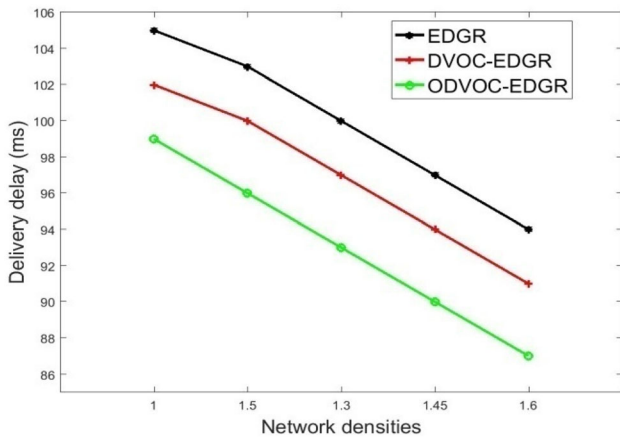


Fig. 2 DD vs. network densities

Table 4 Comparison of EC vs. network densities

Network densities	EDGR	DVOC-EDGR	ODVOC-EDGR
1	2.8	2.75	2.7
1.15	2.72	2.67	2.62
1.3	2.64	2.59	2.54
1.45	2.6	2.55	2.5
1.6	2.57	2.52	2.47

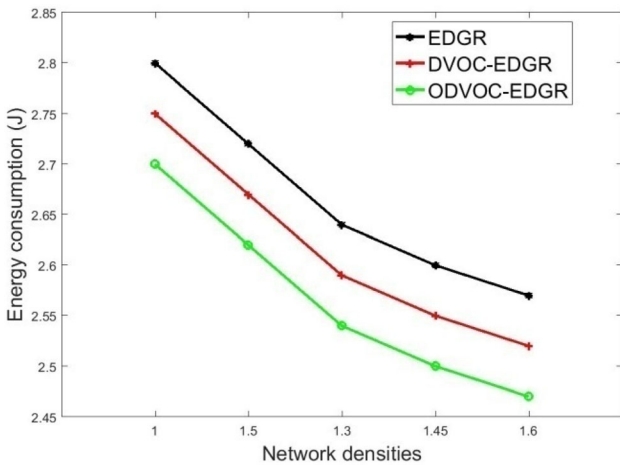


Fig. 3 EC vs. network densities

$$E_f(u, d) = E_f^{op} = \|w(u) - w(d)\| \tag{9}$$

In Eq. (9), $w(u)$ and $w(d)$ are 2D locational vectors for the moving nodes u and v . This function normally computes the Euclidean norm. While u and d are close to each other, the observed undesirability measure $E_f(u, d)$ becomes small which reduces the time taken for the water drop to travel from move u to v . When the water drop travels from one node to another, it brings a quantity of soil

Table 5 Comparison of NL vs. network densities

Network densities	EDGR	DVOC-EDGR	ODVOC-EDGR
1	322	327	332
1.15	330	335	340
1.3	335	340	345
1.45	340	345	350
1.6	348	353	358

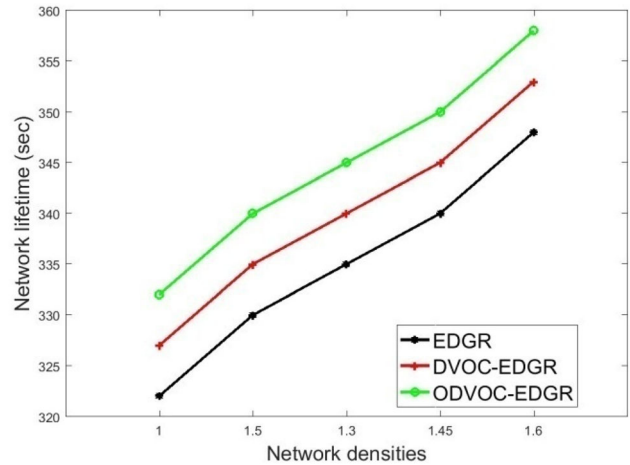


Fig. 4 NL vs. network densities

within it. The quantity of soil passed is inversely proportional to the time taken by the water drop for arriving at the destination. The quantity of soil i.e., $MSG(u, d)$ carried by water drop is computed as:

$$\Delta MSG(u, d) = \frac{a_{vc}}{b_{vc} + c_{vc}(\text{time}(u, d; V^{ud}))} \tag{10}$$

In Eq. (10), $\Delta MSG(u, d)$ denotes the amount of MSG neglected by the water drop travelling from node u to d . Besides, a_{vc} , b_{vc} and c_{vc} are constant velocity parameters. After the water drops travel between node u and d , MSG between them is minimized by,

Table 6 Comparison of PDR vs. energy hole sizes

Energy hole sizes	EDGR	DVOC-EDGR	ODVOC-EDGR
50	0.958	0.961	0.965
60	0.95	0.954	0.959
70	0.942	0.946	0.951
80	0.93	0.934	0.939
90	0.91	0.918	0.923
100	0.88	0.89	0.895

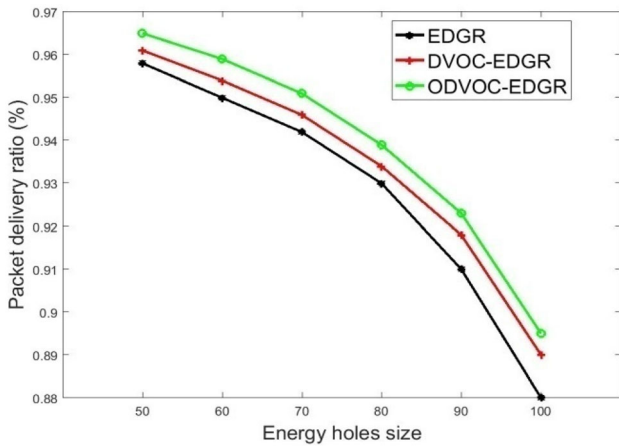


Fig. 5 PDR vs. energy holes size

$$MSG(u, d) = \rho_0 \cdot MSG_t(u, d) - \rho_n \cdot \Delta MSG(u, d) \quad (11)$$

In Eq. (11), ρ_0 and ρ_n are positive numbers selected between 0 and 1. The water drop that has traveled from u to v can increase the MSG transfer MSG^{ud} by:

$$MSG^{ud} = MSG^{ud} + \Delta MSG_t(u, d) \quad (12)$$

The most significant property of IWD is choosing a route with less quantity of soil (packet transfer) than other routes. This is achieved by transferring on a chance to each node except the current node. The probability ($\mathcal{P}_u^{ud}(d)$) of water drop moving from u to d is computed by:

$$\mathcal{P}_u^{ud}(d) = \frac{f(MSG_t(u, d))}{\sum_{k \notin y^{ud}} f(MSG_t(u, k))} \quad (13)$$

In Eq. (13), y^{ud} is the node that the water drop must not stay to remain the conditions and $f(MSG_t(u, d))$ determines the inverse of the MSG between the node u and d as:

$$f(MSG_t(u, d)) = \frac{1}{\epsilon_m + MSG_t(u, d)} \quad (14)$$

In Eq. (14), the value of the parameter $\epsilon_m = 0.01 \times g(MSG_t(u, d))$ is used for shifting $MSG(u, d)$ on the path

Table 7 Comparison of DD vs. energy hole sizes

Energy hole sizes	EDGR	DVOC-EDGR	ODVOC-EDGR
50	85	81.5	78.8
60	87.5	85	82.5
70	92.5	89.8	86.1
80	94.8	91.5	88.9
90	97.5	95.6	92.5
100	103	100.7	97.4

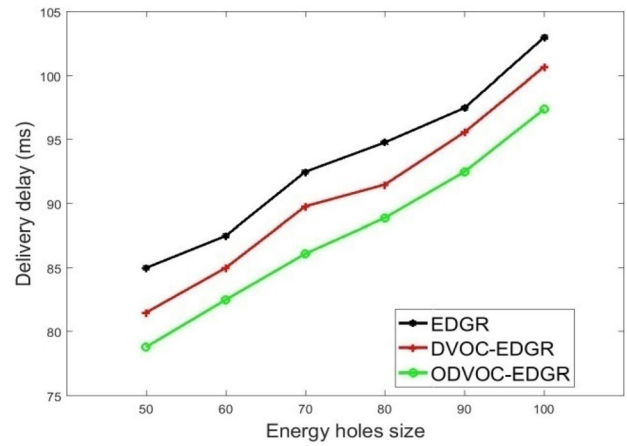


Fig. 6 DD vs. energy holes size

Table 8 Comparison of EC vs. energy hole sizes

Energy hole sizes	EDGR	DVOC-EDGR	ODVOC-EDGR
50	2.78	2.74	2.70
60	2.81	2.77	2.73
70	2.98	2.94	2.90
80	3.02	2.98	2.94
90	3.18	3.14	3.10
100	3.21	3.17	3.14

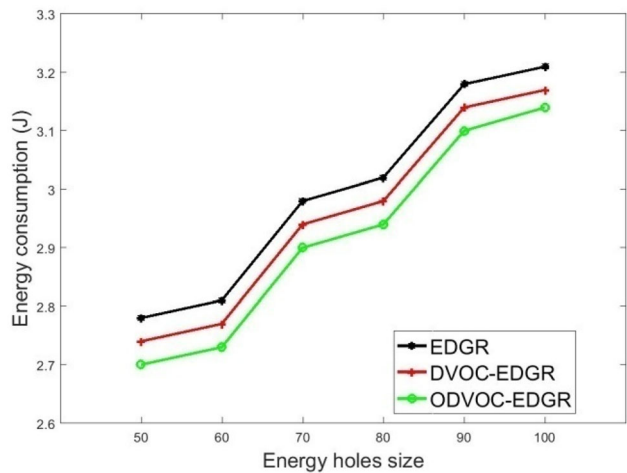


Fig. 7 EC vs. energy holes size

linking u and d towards progressive results and $g(MSG_t(u, d))$ is computed as:

$$g(MSG(u, d)) = MSG(u, d) - \min_{l \notin y^{ud}} MSG(u, l) \quad (15)$$

This function must be used to determine an approximation of the solution i.e., shortest moving distance. The best shortest moving distance (D^m) is computed by $n(D^m)$.

Table 9 Comparison of NL vs. energy hole sizes

Energy hole sizes	EDGR	DVOC-EDGR	ODVOC-EDGR
50	320	325	330
60	316	321	326
70	310	315	320
80	306	311	316
90	300	305	310
100	294	299	305

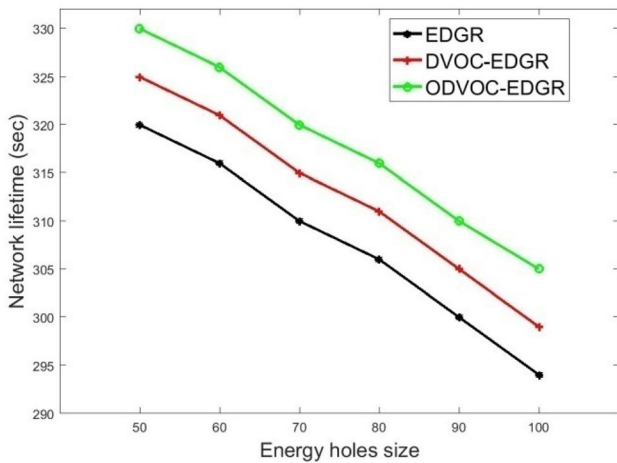


Fig. 8 NL vs. energy holes size

Table 10 Comparison of PDR vs. communication sessions

Communication sessions	EDGR	DVOC-EDGR	ODVOC-EDGR
1	0.98	0.983	0.985
2	0.97	0.973	0.976
3	0.965	0.968	0.971
4	0.958	0.961	0.964
5	0.952	0.955	0.958

This process terminates iteration while all water drops have discovered their solution. The overall best shortest moving distance is determined by,

$$D^{best} = \underset{\forall D^m}{\operatorname{argmin}}(D^m) \tag{16}$$

Thus, the best solution is the shortest moving distance that minimizes the sum of all moving paths from source to destination is obtained.

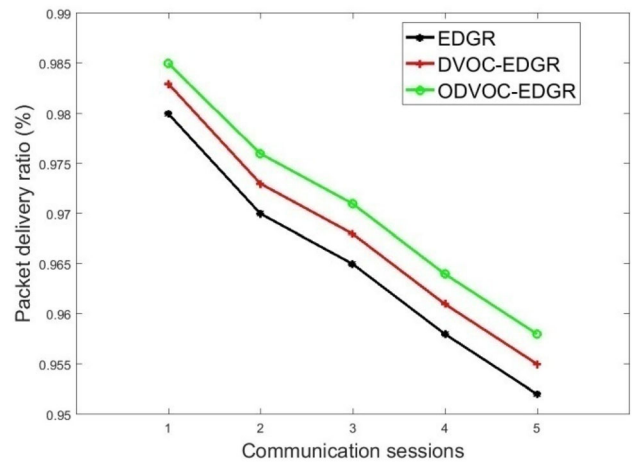


Fig. 9 PDR vs. communication sessions

Table 11 Comparison of DD vs. communication sessions

Communication sessions	EDGR	DVOC-EDGR	ODVOC-EDGR
1	82	79	76
2	85	82	79
3	88	85	82
4	93	90	87
5	94	91	88

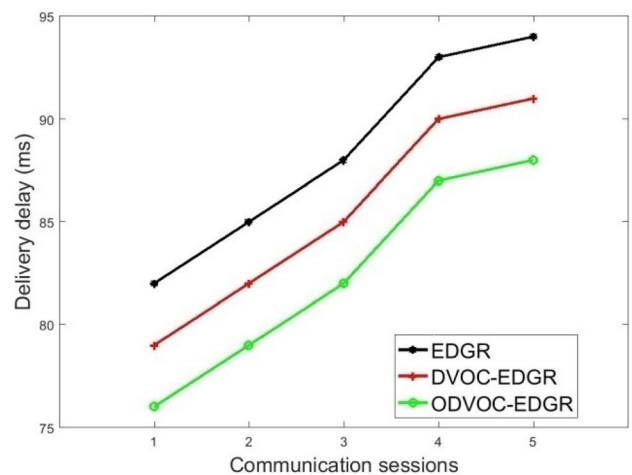


Fig. 10 DD vs. communication sessions

4 Performance analysis

In this segment, the simulation outcomes of the proposed protocols DVOC-EDGR and ODVOC-EDGR are presented which are compared with the existing EDGR using Network Simulator (NS-2.34). The analysis is performed under three basic scenarios such as varying network

Table 12 Comparison of EC vs. communication sessions

Communication sessions	EDGR	DVOC-EDGR	ODVOC-EDGR
1	2.24	2.21	2.18
2	2.25	2.22	2.19
3	2.32	2.30	2.27
4	2.34	2.32	2.29
5	2.5	2.47	2.44

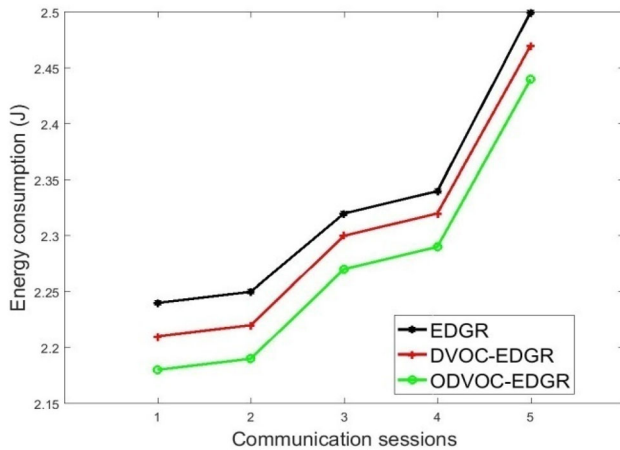


Fig. 11 EC vs. communication sessions

density, energy holes size and communication sessions. The parameters used in this experiment are listed in Table 1.

For performance evaluation, different metrics including PDR, DD, EC, and NL are utilized.

- PDR: It refers to the percentage of the amount of effectively received packets at the destination to the number of packets sent from the source.
- DD: It refers to the time delay from the creation of packets to its reception at the destination.
- EC: It refers to the overall power used by the nodes that join in data transmission.

Table 13 Comparison of NL vs. Communication Sessions

Communication sessions	EDGR	DVOC-EDGR	ODVOC-EDGR
1	420	431	442
2	404	413	426
3	390	405	414
4	384	392	403
5	380	394	405

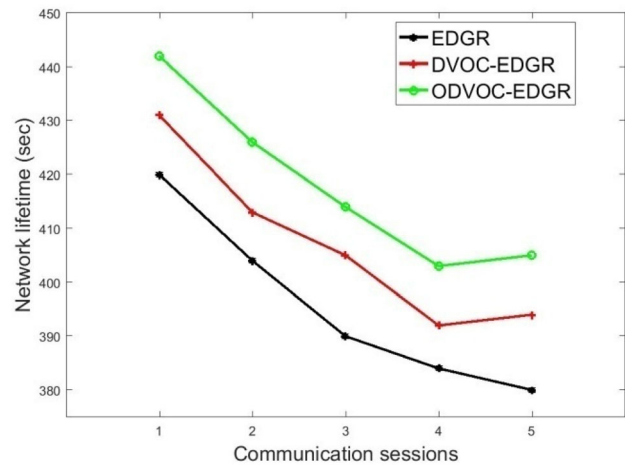


Fig. 12 NL vs. communication sessions

- NL: It refers to the time taken from simulation establishing to the interval that nodes exhaust their 20% or more power in the network.

4.1 Analysis of varying network density scenario

Performance of the existing and proposed schemes is evaluated on the basis of network density. Variance in network density provides varied simulation analysis and provides accurate result for the simulation (Table 2).

Figure 1 illustrates the PDR of proposed and existing protocols with different network densities. It shows that if the network density is 1.6, then the PDR of ODVOC-EDGR protocol is 1.44% greater than EDGR and 0.51% greater than DVOC-EDGR. Therefore, it is observed that the ODVOC-EDGR increases PDR compared to the other protocols (Table 3).

Figure 2 shows the DD of DVOC-EDGR, ODVOC-EDGR, and EDGR with different network densities. It shows that if the network density is 1.6, then the DD of ODVOC-EDGR is 7.45% less than EDGR and 4.4% less than DVOC-EDGR. Thus, it is observed that the ODVOC-EDGR minimizes DD than the DVOC-EDGR and EDGR (Table 4).

Figure 3 demonstrates the EC of DVOC-EDGR, ODVOC-EDGR, and EDGR under various network densities. It shows that if the network density is 1.6, then the EC of ODVOC-EDGR is 3.89% minimized than EDGR and 1.98% minimized than DVOC-EDGR. Therefore, it is observed that the ODVOC-EDGR minimizes the EC than the other protocols (Table 5).

Figure 4 illustrates the NL of DVOC-EDGR, ODVOC-EDGR, and EDGR with different network densities. It shows that if the network density is 1.6, then the NL of ODVOC-EDGR is 2.87% higher than EDGR and 1.42%

higher than DVOC-EDGR. Hence, it is observed that the ODVOC-EDGR achieves higher NL compared to the DVOC-EDGR and EDGR (Table 6).

4.2 Analysis of varying energy holes sizes scenario

Figure 5 illustrates the PDR of proposed and existing protocols with different energy holes sizes. It shows that if the energy holes size is 50, then the PDR of ODVOC-EDGR is 0.73% higher than EDGR and 0.42% higher than DVOC-EDGR. Therefore, it is observed that the ODVOC-EDGR achieves high PDR than the other protocols (Table 7).

Figure 6 illustrates the DD of DVOC-EDGR, ODVOC-EDGR, and EDGR with varied energy holes size. It shows that if the energy holes size is 50, then the DD of ODVOC-EDGR is 7.29% less than EDGR and 3.31% less than DVOC-EDGR. Thus, it is observed that the ODVOC-EDGR has reduced DD than the DVOC-EDGR and EDGR (Table 8).

Figure 7 demonstrates the EC of proposed and existing protocols with different energy holes size. It shows that if the energy holes size is 50, then the EC of ODVOC-EDGR is 2.88% reduced than EDGR and 1.46% reduced than DVOC-EDGR. Thus, it is observed that the ODVOC-EDGR minimizes the EC than the other protocols (Table 9).

Figure 8 illustrates the NL of DVOC-EDGR, ODVOC-EDGR, and EDGR with varied energy holes size. It shows that if the energy holes size is 50, then the NL of ODVOC-EDGR is 3.13% higher than EDGR and 1.54% higher than DVOC-EDGR. Therefore, it is observed that the ODVOC-EDGR achieves higher NL compared to the DVOC-EDGR and EDGR (Table 10).

4.3 Analysis of varying communication session scenario

Figure 9 illustrates the PDR of proposed and existing protocols with different communication sessions. It shows that if the number of the communication session is 5, then the PDR of ODVOC-EDGR is 0.63% higher than EDGR and 0.31% higher than DVOC-EDGR. Thus, it is observed that the ODVOC-EDGR increases PDR than the other protocols (Table 11).

Figure 10 demonstrates the DD of DVOC-EDGR, ODVOC-EDGR, and EDGR with different communication sessions. It shows that if the number of communication session is 5, then the DD of ODVOC-EDGR is 6.38% less than EDGR and 3.3% less than DVOC-EDGR. Hence, it is observed that the ODVOC-EDGR minimizes DD than the DVOC-EDGR and EDGR. Effective discovery of energy

holes and proper monitoring of nodes in network has prevented the formation of new holes that is achieved by the proposed algorithm (Table 12).

Figure 11 illustrates the EC of proposed and existing protocols with varied communication sessions. It shows that if the number of the communication session is 5, then the EC of ODVOC-EDGR is 2.4% less than EDGR and 1.21% less than DVOC-EDGR. Thus, it is observed that the ODVOC-EDGR protocol minimizes the EC than the other protocols (Table 13).

Figure 12 demonstrates the NL of DVOC-EDGR, ODVOC-EDGR, and EDGR with different communication sessions. It shows that if the number of communication session is 5, then the NL of ODVOC-EDGR is 6.58% higher than EDGR and 2.79% higher than DVOC-EDGR. Hence, it is observed that the ODVOC-EDGR has high NL compared to the DVOC-EDGR and EDGR.

5 Conclusion

In this article, an optimized distributed collaboration mechanism is proposed with EDGR for k -coverage energy holes detection and healing in WSN that minimizes the DD. Initially, DVOC-EDGR method is applied in which the nodes can cooperate in energy holes detection and recovery. By using this method, LVDs are constructed and the nodes are enabled to monitor each other node's critical locations around themselves. Moreover, an ODVOC-EDGR protocol is proposed that uses IWD algorithm to find the globally optimized routes for decreasing the DD. Finally, the simulation outcomes show that the ODVOC-EDGR protocol minimizes EC, DD and increases NL, PDR than the DVOC-EDGR and EDGR protocols under varied network densities, energy holes sizes and communication sessions.

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and Internet of Things.

M. Sridhar has completed M.Sc in Computer Science. He is currently pursuing his PhD in computer science in the school of Computer Science and Engineering, Bharathiar University, Coimbatore, Tamil Nadu, India. He has published research papers in International Journals and presented papers in International and National Conference. He has published one book chapter. His area of specializations and research interest are Wireless Sensor Network



P. B. Pankajavalli PhD is an Assistant Professor in the Department of Computer Science, School of Computer Science and Engineering, Bharathiar University, Coimbatore, Tamil Nadu, India. She is carrying out a funded project of Rs. 24 lakhs in the domain Sensor Networks. She has published more than 40 papers in journals, Conferences proceedings both at National and International level, 4 book chapters, and one edited book and filed an Indian patent. She has received Best Teacher Award from Lions Club, Erode. Her areas of interest include Ad-hoc Networks, Wireless Sensor Networks and Internet of Things.