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Evaluation of Graph Routing Single Objective Paths Using Pre-set Unequal Clustering

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Abstract*— Multi-hop network paths and path redundancy enhance the reliability of communications in the Graph Routing of Industrial Wireless Sensor Networks (IWSNs). However, the centralised management of IWSNs creates unbalanced energy consumption between battery-powered wireless sensor nodes. This creates a hotspot challenge in Graph Routing. The inability to balance energy consumption with single-objective paths in mesh topologies was revealed in our previous work that used the Covariance-Matrix Adaptation Evolution Strategy (CMA-ES) to improve Graph Routing [1]. In this paper, we address this problem by combining the single-objective paths of the Graph Routing algorithm with a pre-set unequal clustering topology. First, this study detects isolated nodes within pre-set unequal clustering and then creates new clusters for these nodes. Second, the objective function of CMA-ES is used to select the best cluster head by considering node centrality between the nodes in the same cluster and the distance between other cluster heads or the gateway. Once the cluster heads are selected, single-objective paths of Graph Routing that are minimum-distance (PODis), maximum residual energy (POEng), and minimum end-to-end transmission time (POE2E) can be effectively evaluated. Simulation experiments reveal that using the single-objective paths of Graph Routing by the topology of pre-set unequal clustering results in more balanced energy consumption.

Keywords—IWSNs, Graph Routing, unequal clustering, CMA-ES, best cluster head.

I. INTRODUCTION

Given the self-organising and self-healing capabilities of Industrial Wireless Sensor Networks (IWSNs) alongside their low deployment costs and flexibility, it comes as no surprise that the fields of Industry 4.0 and the Industrial Internet of Things (IIoT) have taken heightened interest in such networks [2]. The network gateway (G_w) is linked to centralised Network Manager (NM) which receives data packets transferred from sensor nodes as per the standard configuration of IWSN paths [3]. IWSN applications use WirelessHART, ISA 100.11a, and WIA-PA standards but face strict challenges due to interference, noise, and physical obstacles present in industrial environments [2], [3]. The typical topology comprises a mesh network where wireless sensor nodes are limited-battery powered and small [4].

Every sensor node can function as a router for data packets from other sensor nodes within the mesh topology. Thus, a sensor node transmits its data packet to the closest neighbouring sensor node rather than communicating with G_w [4]. Hence, on top of the fundamental functions of a sensor node, routing and the forwarding of data packets determine the battery life of the wireless sensor node. A *hop* signifies each individual movement of a data packet on the path from one sensor node to another. *Multi-hop* transmission may be required for a data packet to reach G_w from its source node [5].

A lack of balance in energy consumption can result when sensor nodes close to the G_w receive data packets from all sensor nodes in the network. This so called "*hotspot problem*" is induced by the centralised management of IWSNs [5]. In other words, nodes distant from the G_w require significantly less energy consumption than those close to it. Ultimately, partitioning of the network is a possibility due to the hotspot problem, as sensor nodes near the G_w may expire much faster than sensor nodes further away from the G_w due to unbalanced energy consumption [5]. Consequently, the balance of energy consumption among the nodes is a key factor that must be taken into account when executing the IWSN's energy-saving procedures.

Given that resource usage, energy consumption, communications reliability, and latency of the network are all impacted by routing, it is evident that routing embodies a critical function in IWSNs [3]. The objective of the balance of energy consumption largely depends on the Graph Routing (GR) algorithm, which is the principal routing method in IWSN standards [3], [6]. The GR algorithm implements the first-path approach with path redundancy for the transmission of data packets to the G_w from a source node [3], [7].

As mentioned, we proposed three paths with a single-objective function using the Covariance-Matrix Adaptation Evolution Strategy (CMA-ES) [1] based on the requirements of IWSNs. These are: the path based on the minimum distance between sensor nodes in the direction of the G_w (PODis); the path based on maximum residual energy (POEng); and the path based on minimum end-to-end transmission time (POE2E). We observed that single-objective paths of GR did not achieve balanced energy consumption and can cause hotspot problem in the network area.

Therefore, pre-set unequal clusters divide the network area into several unequal clusters in size, and each cluster has a cluster head (CH) that performs data packet forwarding from sensor nodes in its cluster to the G_w. CHs remote from the G_w can have more members than those close to the G_w [5]. Considering that receiving and routing packets consume large amounts of energy, distant CHs would not need to forward many packets and hence unequal clusters could result in more balanced energy consumption.

To optimise the balance of energy consumption in the paths mentioned above, this paper will evaluate the three single-objective paths with a pre-set unequal clustering topology, which is the WirelessHART Density Controlled Divide-and-Rule (WDDR) [5] algorithm. The WDDR algorithm could aid in balancing energy consumption through reducing overhead on sensor nodes around the G_w, which results in reduced energy consumption for these nodes and improved network topology. However, due to its static approach, we observed a special phenomenon in WDDR, namely *isolated nodes*, which are the nodes that are incapable of communicating with other sensor nodes in the same cluster. This phenomenon appeared in the farther away clusters from the G_w as these tend to be bigger than those closer to the G_w [5].

The main contributions of this paper:

1. Detection of isolated nodes in the WDDR algorithm in each static cluster enables lost data packets and latency to be overcome by creating new clusters for these nodes.

2. The CMA-ES [8] is used for selecting the CHs in the IWSN due to its high stability and lower computational complexity. In this study, CMA-ES selects the CH based on two objective functions, which are: node centrality in the same cluster; and minimum distance to the gateway (if it is within the latter's communication range) or to other CHs in the G_w direction (if the G_w is outside its communication range).

3. Evaluate the PODis, POEng, and POE2E paths for the GR algorithm for data packet transmission from CHs to the G_w. This is the inter-cluster communication that creates paths from the CH to the G_w as a single hop or from the CH to other CHs in the direction of the G_w as a multi-hop route.

The ensuing sections of this paper comprise the related work and a description of the proposed technique involving the amalgamation of single objective paths of Graph Routing and pre-set unequal clustering in Sections II and III, respectively. The simulation format and the performance evaluation are discussed in Section IV and the conclusions in Section V.

II. Related Works

Improvements to the performance of routing algorithms in Wireless Sensor Networks (WSNs) are especially notable via the use of optimisation techniques that represent a significant paradigm for enhancing such WSNs. The intended purposes of optimization may vary with the objectives to be met, such as maximising efficiency, enhancing performance or reducing energy consumption.

In our work [1], which is the first of its kind to use optimisation techniques in IWSNs, the GR paths of the mesh topology were selected using the CMA-ES in order to enhance the GR algorithm of the IWSNs according to the requirements of IWSN monitoring systems. These requirements consist of low end-to-end transmission time, balanced energy consumption, and high communication reliability. The inability to attain a balance of energy consumption by best single paths of GR is highlighted in this study. Therefore, the approach of improving the paths of GR by optimisation techniques with a single objective is inadequate in IWSNs, as they may still suffer from unbalanced energy consumption.

Recently, many researchers (e.g., [9]–[11]) have used optimisation techniques to improve routing algorithms in WSNs by using clustering methods. Optimisation techniques help in improved clustering formation, selecting optimal CHs based on specific objective functions and re-clustering. Additionally, performance is enhanced, delays are reduced, and energy consumption is diminished in routing algorithms by the use of clustering methods.

The degree of a node, the residual energy, the initial energy of the node, and the distance to the base station comprise the four factors through which optimal CHs are selected using fruit fly and genetic algorithms to address the issue of unbalanced energy consumption in [9]. These algorithms are implemented to cluster the nodes in the network, while to determine the optimal path the Dijkstra algorithm is applied [12]. A 10% rise in the total network coverage and a 50% enhancement of the network lifetime are outcomes of the mentioned amalgamation of algorithms.

The authors in [10] explain how optimisation algorithm concepts are used in networks that require cluster-based transmission schemes to increase or boost routing optimisation in WSNs. They are using the cuckoo optimisation algorithm for selecting effective CHs based on four criteria, namely the remaining energy of nodes, distance to the base station, intra-cluster distances, and inter-cluster distances. The energy consumption balance across the network nodes is sustained while the data packet delivery rate is enhanced through this approach.

Increasing the lifetime of the network and diminishing the total energy consumption were objectives of a separate study that utilised two optimisation techniques—the ant colony optimisation (ACO) and the butterfly optimisation algorithm (BOA)—in combination with clustering to form a routing algorithm [11]. Given the diminished computational complexity and high stability of BOA, the technique was used to choose the CH within the WSN. On the other hand, the capability to rapidly find solutions in a WSN led to the use of the ACO in determining the optimal path between the CH and the base station from several objective functions. By using clustering to attain overhead routing, the mentioned work demonstrates diminished energy consumption and enhanced throughput via an amalgamation of techniques.

III. The Proposed Method

The deficiencies of using single-objective paths for Graph Routing in an IWSN mesh topology were presented in [1]: unbalanced energy consumption leading to hotspots; low coverage; short lifetime of the network among others. To address these challenges, the proposed method principally evaluates best single-objective paths using pre-set unequal clustering. The flowchart in Fig. 1 illustrates this concept in more detail.

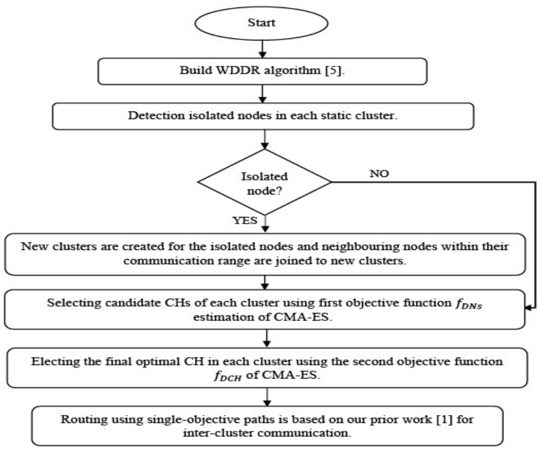


Fig. 1. Flowchart of the proposed methodology.

A. Clustering Formation Stage

Balanced energy consumption in this work is achieved by using the pre-set unequal clustering process, as seen in the WDDR algorithm [5]. Then, the isolated sensor nodes are initially detected in each static cluster in the WDDR algorithm based on the communication range of sensor nodes in the same cluster. Using Algorithm 1, a new cluster is made based on the location of these nodes. Then, candidates for efficient CHs are selected based on their location in relation to other CHs and the centrality of the node in the cluster.

B. Detection of isolated sensor nodes in each static cluster

As illustrated in the pseudo-code in Algorithm 1, the proposed technique makes it possible to find isolated nodes from the static approach of the pre-set unequal clustering of the WDDR algorithm [5] and create new clusters for them.

Algorithm 1: Detection isolated sensor nodes in the clusters.

Input: Main Static Clusters.

Output: New Clusters of isolated sensor nodes.

1. ***For*** Main Static Clusters
2. *Find distances between nodes in each static clusters.*
3. $Check\ (nodIsolated\ <= CommunicationRange);$
4. $\boldsymbol{If}\ nodIsolated$
5. $\quad Define\ the\ cluster\ which\ has\ an\ Isolated\ node.$
6. $\quad Calculate\ means\ of\ this\ cluster.$
7. $\boldsymbol{If}\ mod(nodIsolated) == 0$
8. $\qquad Means\ result\ is\ even\ for\ vertical\ cluster.$
9. $\qquad Looking\ for\ the\ y\ positions\ to\ separationY.$
10. $\qquad Add\ sensor\ nodes\ in\ new\ clusters.$
11. $\boldsymbol{Else}$
12. $\qquad Means\ result\ is\ odd\ for\ horizontal\ cluster.$
13. $\qquad Looking\ for\ the\ x\ positions\ to\ separationX.$
14. $\qquad Add\ sensor\ nodes\ in\ new\ clusters\ .$
15. $\boldsymbol{End}$
16. $Select\ Cluster\ Heads\ using$
17. $\qquad \boldsymbol{Objective\ Functions\ of\ CMAES}$
18. $\boldsymbol{End}$

Algorithm 1 carries out this function, as demonstrated in lines 1-6 regarding the identification of isolated nodes in every static cluster. First, it defines the Euclidean distance between sensor nodes in the same cluster, and then it checks if there is any sensor node outside the communication range of other nodes in the same cluster. An isolated node is determined in the case where a sensor node is incapable of communicating with another sensor node. The goal is that when selecting any node as a CH, it can communicate with any other sensor node in its cluster.

The mean location of an isolated node is calculated, as seen in lines 7–14 which, in turn, serves as the basis for the generation of the new cluster. This effectively necessitates the capacity of all sensor nodes within the same cluster to communicate with one another.

The WDDR algorithm divides static clusters into vertical and horizontal clusters as shown in Fig. 2a, where C1, C2, ..., and C9 are the number of clusters. Hence, sensor nodes close to the isolated nodes within its communication range in the new cluster are incorporated following the generation of the new cluster, which, in turn, is based upon the location mean of the coordinates of the isolated node. This is exemplified by C9 dividing into two clusters to generate a new cluster for node 37 as it is incapable of communicating with sensor nodes 5, 24, 26, and 36, thereby making it an isolated node, as portrayed in Figure 2b. Finally, the CMA-ES algorithm is used to select the best CHs from each cluster. The following section expands on this process.

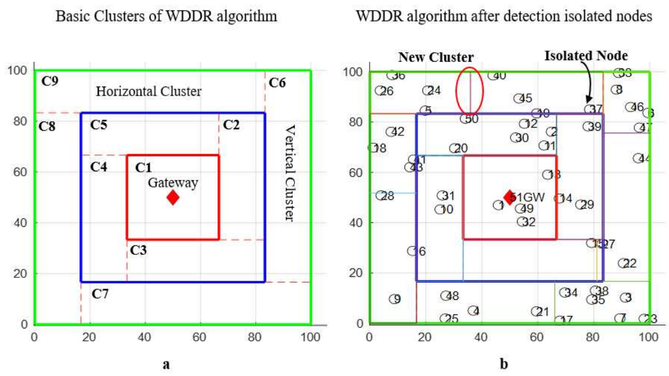


Fig. 2. WDDR algorithm before and after detection isolated node.

C. Optimisation of Cluster Heads Selection

An appropriate selection of CHs needs to be considered in this type of clustering because of its static approach. This affects communication with the nodes in their own cluster and other CHs or the G_w in IWSNs. It is noted that energy consumption is diminished when the transmission distance is shorter [11].

Therefore, the final CHs are selected using CMA-ES based on two steps: First, tentative CHs are selected for each cluster using node centrality. Second, the best CH is chosen based on its location in relation to the G_w or other CHs. To diminish the overhead of the network, rather than altering the CHs in each round, CHs are re-selected via the same stages when they consume half their initial energy, which represents the energy threshold.

Initially, several tentative CHs are selected in each cluster to compete for the role of actual CH. This uses the first objective function f_{DNs} of CMA-ES, which selects tentative CHs that are sensor nodes central to their own neighbour nodes in the same cluster. Other nodes keep sleeping until the CH selection phase ends.

Suppose node i becomes a tentative CH, called s_i. s_i has a second objective function f_{DCH}, which is a function of its distance to the G_w and other CHs that we will discuss later. Our goal is that if s_i becomes a CH at the end of the competition, this will be the best CH based on the CMA-ES algorithm where best CHs are situated most proximally to their neighbours, the G_w, or other CHs. The reason for this is to reduce energy consumption, minimise time delays and improve communication reliability. Equation 1 is used to choose node centrality as per the first objective function f_{DNs} of CMA-ES:

1) Node centrality: The extent to which a CH is situated centrally in relation to neighbouring nodes in the same cluster is representative of the node's centrality. The length of the transmission path largely determines the energy dissipation of the node. When the chosen node possesses less transmission distance towards G_w, the energy consumption of the node is smaller [11]. The distance from CH to the normal sensors is illustrated below:

$$f_{DNs} = Minmum \sum_{j=1}^{m} (\sum_{i=1}^{I_j} dis(s_i\,, CH_j))/I_j \qquad (1)$$

Where the number of sensor nodes pertaining to CH and the distance between sensor node CH_j and i are signified by I_j and $dis(s_i, CH_j)$, respectively.

Additionally, the best CHs should support inter-cluster communication, whether with the gateway or other CHs, to deliver the data packets to the G_w; not all tentative CHs can necessarily communicate with the G_w or other CHs. We need to control the distance between CHs capable of directly communicating with the G_w or other CHs through the selection of best CH which reside at the minimum communication distance. The second objective function f_{DCH} of CMA-ES algorithm serves as the basis for the control of distance and the selection of best CHs.

2) Minimum distance between the CHs and the G_w: First, each tentative CH checks if it can connect directly with the G_w; if not, it will check the distance between itself and other CHs closer to the G_w. The distance of the transmission path determines the energy consumption of the node. For instance, the CH requires more energy for data transmission when the G_w is situated far away from it. Thus, the sudden drop in CH's energy may occur due to higher energy consumption. Hence, the node with a lesser distance from the G_w is preferred during data transmission [11]. Equation (2) below demonstrates the objective function of distance between the G_w and the CH:

$$f_{DCH} = Minmum \sum_{i=1}^{m} dis(CH_i\,, G_w) \qquad (2)$$

Where, the term $dis(CH_i,\, G_w)$ represents the distance between G_w and CH_i.

D. Communication Stage

There are two phases to forward data between the G_w and sensor nodes following the establishment of unequal clustering in the network area.

Intra-cluster paths are enacted by direct communication as a single hop where each member sensor node in the cluster connects to its CH to transmit its respective data packets within the first phase.

In the second phase, GR builds best single objective paths using the CMA-ES between CHs for transmitting data packets to the G_w by using multi-hop communication between them, which is called inter-cluster paths.

To save the energy of sensor nodes around the G_w and achieve balanced energy consumption, a CH in any cluster can communicate directly with the G_w if it is within its communication range, without the need to forward data packets through CHs around the G_w.

IV. Simulation Experiments

A. Simulation Setting

Simulations were conducted using MATLAB R2021b on a Windows 10 workstation running on an Intel(R) core™ i7 processor with 16 GB RAM. The simulation parameters are presented in the table below and are similar to those used in our prior work [1], [5].

50 or 100 sensor nodes were employed in order to verify the performance of the POE2E, POEng and PODis, respectively, under varying node densities and random deployment. Since each run of the simulation presented a different deployment with respect to the spatial distribution of the sensor nodes, the performance metrics generated were for different values. Several simulations were therefore conducted in order to verify whether the POE2E, POEng and PODis produced similar performance levels over 15 random deployments and to obtain statistical means for the results. In this work, the performance of best single-objective paths of the GR algorithms was measured by the packet delivery ratio (PDR), packet miss ratio (PMR), total consumed energy, energy imbalance factor (EIF), and end-to-end transmission (E2ET), respectively.

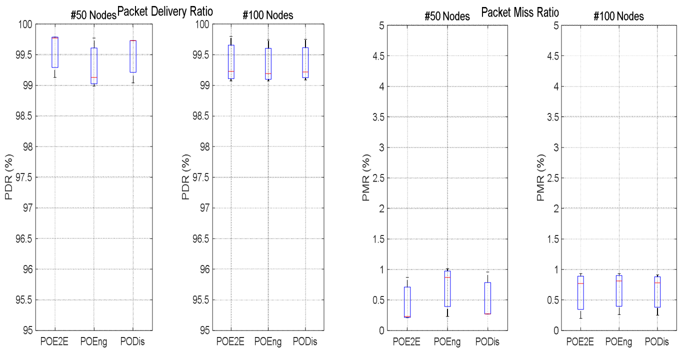
TABLE I. SYSTEM PARAMETERS.

Parameters	Value
Node and area parameters	
Simulation area	$100 \times 100\ m^2$
Number of nodes	50 and 100.
Nodes positions	Random.
G_w position	Central.
Unequal clustering algorithms	WDDR [5].
Number of rounds	10000.
Physical Layer	
Physical layer	IEEE 802.15.4 (2006).
Propagation Model	O-QPSK.
Communication range	35 meters.
Transmission power	0 dBm.
Node initial energy	0.5 J.
Maximum Packet size	133 Bytes.
Radio frequency	2.4 GHz.
Medium Access Control (MAC)	TDMA with 10 ms time slot.
Network layer	
Routing algorithm	POE2E, POEng and PODis [1].
CMA-ES parameters	
Population size (λ)	$4 + \lfloor 3\log(n) \rfloor$.
Number of the variables (n)	Shortlist.
Specifies the direction (σ)	$0.3 * (VarMax - VarMin)$.
$VarMax$	Upper bound to the Shortlist decision.
$VarMin$	Lower bound to the Shortlist decision.

B. Evaluation Results and Analysis

1) Network Reliability evaluation: The two critical factors used to evaluate the reliability of the network in this research were the PDR and PMR, as shown in Fig. 3. As the delivery of data packets to the G_w increases, the PMR decreases.

Fig. 3 demonstrates that the best single-objective paths of the GR algorithm with a pre-set unequal clustering topology had a higher PDR and a lower PMR than the mesh topology in [1], which indicated that more data packets reached the G_w. The proposed method facilitated a decrease in the ratio of missing data packets and an improvement in the communication reliability of the entire network. This is expected, due to the mitigation of isolated nodes, the use of path redundancy, and the selection of the best CH in each cluster based on the minimum distance from the source sensor node to the gateway using the CMA-ES.



(a) (b)

Fig. 3. PDR and PMR boxplots for topology examples: (a) PDR of 50 and 100 nodes; (b) PMR results of 50 and 100 nodes.

In the small network of 50-sensor nodes depicted in Fig. 3, it was noticed that the number of data packets received at the G_w was only marginally decreased by 0.6% in the POEng of the GR algorithm compared to the POE2E and PODis. In general, when the number of sensor nodes increases in the GR algorithm, the PDR may decrease by approximately 0.65% in the GR algorithm POE2E and PODis due to the presence of link failures and congestion routing.

2) Energy Consumption Evaluation: The performance of the proposed POE2E, PODis and POEng were evaluated with respect to energy consumption in terms of both the total consumed energy and the average EIF of the energy balance.

From Fig. 4, we can find that the best single-objective paths in the GR algorithm of the improved WDDR topology optimise the energy consumption of the whole system. This is in comparison to our study [1], where the POEng of the GR with mesh topology consumed more energy because of the increased number of hops along the path. However, the proposed method causes the nodes to consume less energy due to the selection of the best CH with a small distance to the G_w and the centrality node between the member nodes in the same cluster, where reducing the distance will reduce the energy consumption. It not only reduces energy consumption, but also prevents the phenomenon of unbalanced energy consumption, which causes a hotspot problem, as shown in Fig. 5.

When compared to [1], the best single-objective paths of the GR algorithm achieved a good balance of energy consumption with an improved WDDR. The ratios of the standard deviation of the residual energy of the whole sensor nodes in the network are the EIF ratio of the POE2E, POEng and PODis 50-nodes are 11%, 21% and 34%, respectively (Fig. 5). Furthermore, the EIF ratio of the POE2E, POEng and PODis 100-nodes are 12%, 17% and 36%, respectively. Compared to the mesh topology in [1], pre-set unequal clustering clearly optimises single-objective paths of the GR algorithm in achieving the balance in energy consumption between sensor nodes in the network area. This represents the objective of the current work.

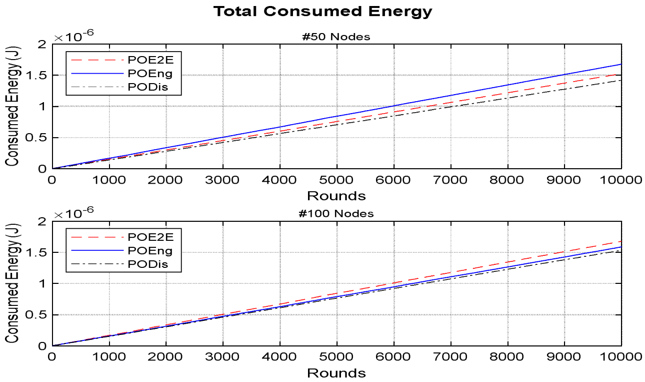


Fig. 4. Total Consumed Energy for Energy consumption results of 50 and 100 sensor nodes.

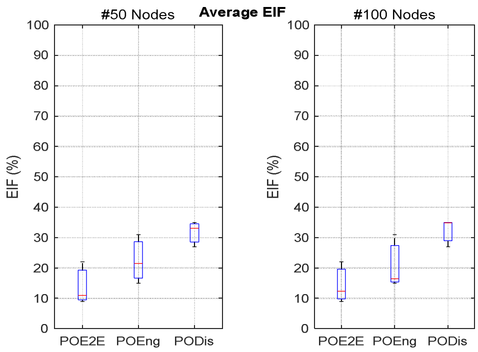


Fig. 5. Energy Imbalance Factor (EIF) results of 50 and 100 sensor nodes.

In the proposed method, two techniques clearly enabled achieving the balance in energy consumption between the sensor nodes in the network area compared to the mesh topology in [1]. Firstly, the pre-set unequal clustering topology facilitated the best single-objective paths of the GR algorithm in order to save the energy of the sensor nodes around the gateway by reducing overheads on these nodes. The second method enabled other CHs which are not in the cluster around the G_w to communicate with the G_w if the G_w was in their communication range, resulting in good load balancing hence also achieving balanced energy consumption.

3) End-to-End transmission time evaluation: A further experiment was conducted in order to examine the proposed approaches in terms of the E2ET time; this is the time taken for sending a data packet from the source sensor node to the G_w. Monitoring systems often have delay needs of fewer than 100 milliseconds, whereas factory automation has stricter delay requirements, ranging from 2 to 25 milliseconds [13].

Fig. 6 and Fig. 7 show the variation in the data packet transmission of the E2ET for the three best single-objective paths of the GR algorithm for a 10,000-round run of each algorithm under 50 and 100 sensor nodes, respectively. Compared to [1], the E2ET in the POE2E and PODis in the pre-set unequal clustering topology was between 7 and 20 milliseconds in each round. This is generally higher than E2ET obtained from a mesh topology, where the E2ET results were between 5 and 12 milliseconds for the POE2E and PODis. This is due to the lower number of sensor nodes in the cluster surrounding the G_w which causes a long wait in the waiting list.

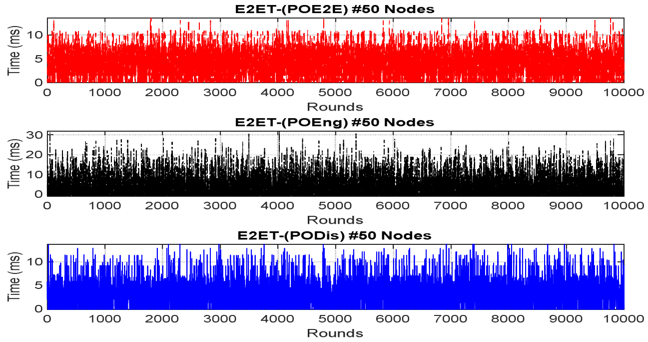


Fig. 6. End-to-End transmission time (E2ET) results of 50 sensor nodes.

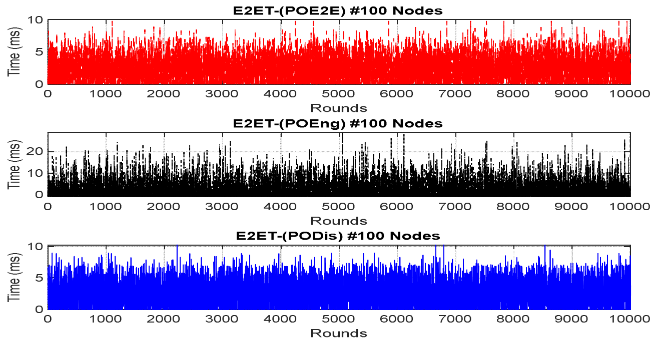


Fig. 7. End-to-End transmission time (E2ET) results of 100 sensor nodes.

It is also noteworthy that the POEng gave lower E2ET results in pre-set unequal clustering than mesh topology, as a result of a reduction in the number of hops in this topology. However, it still exhibited higher transmission time than other best single-objective paths from the GR algorithm. This is expected since, in this proposed method, the best CH with the shortest distance to the member nodes was used either in its own cluster or with other CHs to communicate with the G_w, thus reducing the number of hops when communicating intra-cluster as a single hop. In addition, the CHs could communicate directly with the G_w if the G_w were in their communication range. Finally, each CH can communicate with other CHs in the G_w direction.

V. CONCLUSION

This paper examined how pre-set unequal clustering topology, WirelessHART Density controlled Divide-and-Rule (WDDR), affects the performance of single-objective paths of Graph Routing (GR) that uses the Covariance-Matrix Adaptation Evolution Strategy (CMA-ES). These paths comprise the minimum-distance (PODis), maximum residual energy (POEng) and minimum end-to-end transmission time (POE2E), particularly with regard to the balance of energy consumption. In addition, the WDDR algorithm was improved through reducing the isolated nodes problem in the WDDR algorithm and then using CMA-ES to select the best cluster head (CH) for each cluster.

Using the above optimisation method, the proposed method was examined with respect to the average energy imbalance factor (EIF), packet delivery ratio (PDR), packet miss ratio (PMR), total consumed energy and end-to-end transmission (E2ET). It was discovered that single-objective paths of GR with the improved WDDR algorithm outperformed the mesh topology of these paths in PDR and PMR, significantly improving the network performance and data transmission efficiency. Even though E2ET performed better in the POE2E and PODis mesh topologies, it was best in the POEng with pre-set unequal clustering than in mesh topology. Furthermore, the total consumed energy decreased, achieved by reducing the length of data packet transmission and applying pre-set unequal clustering in order to enhance the balance of energy consumption within the cluster and between clusters.

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