Effect of Unequal Clustering Algorithms in WirelessHART networks

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***Abstract*—The use of Graph Routing in Wireless Highway Addressable Remote Transducer (WirelessHART) networks offers the benefit of increased reliability of communications because of path redundancy and multi-hop network paths. Nonetheless, Graph Routing in a WirelessHART network creates a hotspot challenge resulting from unbalanced energy consumption. This paper proposes the use of unequal clustering algorithms based on Graph Routing in WirelessHART networks to help with balancing energy consumption, maximizing reliability, and reducing the number of hops in the network. Graph Routing is compared with pre-set and probabilistic unequal clustering algorithms in terms of energy consumption, packet delivery ratio, throughput and average end-to-end delay. A simulation test reveals that Graph Routing has improved energy consumption, throughput and reduced average end-to-end delay when conducted using probabilistic unequal clustering algorithms. However, there is no significant change in the packet delivery ratio, as most packets reach their destination successfully anyway.**

Keywords—IWSNs, Graph Routing, unequal clustering, WirelessHART, hotspot problem.

I. Introduction

Industrial Wireless Sensor Networks (IWSNs) gain increasing traction especially in domains such as the Industrial Internet of Things (IIoT) and Industry 4.0 [1]. Accordingly, the worldwide IWSN market size is projected to be $8.67 billion by 2025, with a 50% - 90% reduction in infrastructure costs compared to wired solutions [2]. A typical configuration of IWSN routes transfer packets from sensor nodes to a centralised system, called the Network Manager (NM), which is connected to the network gateway [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. These standards usually result in a mesh network, in which sensor nodes are small and battery powered. They may act in addition to their basic functions; for example, as routers when delivering packets to the gateway to increase the number of communications paths available.

Routing is a significant function in IWSNs, as it influences the communications reliability, energy consumption, latency of the network, and resource usage [3]. In the network layer of WirelessHART, Graph Routing and Source Routing are the two methods proposed for routing packets, each of which is appropriate for a specific use. The goal is to deliver packets on time reliably [4]. This research is focusing specifically on Graph Routing (GR) in WirelessHART networks. GR creates routes with path redundancy providing network reliability in industrial environments. WirelessHART networks support three graph types: broadcasting that enables a gateway to transmit packets into all sensor nodes; downlink that allow the gateway to transmit packets to certain sensor nodes; and uplink, which allows sensor nodes to send packets to the gateway [3]. The GR algorithm in WirelessHART networks is based on a first-path approach available to transmit packets from a source device to a final destination [3], [4]. In general, intermediary sensor nodes within the network will have several neighbouring sensor nodes to send the packets to, and thus, if a sensor node is unable to communicate with one neighbour, it can transmit the packet through an alternative neighbour. The sensor nodes closer to the gateway are overburdened with high traffic loads compared to those further away, as the packets from the entire region are forwarded through the former to reach the gateway. The overloaded nodes will expire much faster than the other sensor nodes because of the imbalance in energy consumption (referred to as the hotspot problem), potentially resulting in partitioning of the network. To mitigate the hotspot problem under energy constraints in WirelessHART networks, balancing energy consumption between sensor nodes is an important target.

A mobile sink node is one proposed solution to mitigate the hotspot effect which can significantly reduce the energy consumption of the sensor nodes and thus improve network lifetime. The premise in [5], [6] is that the mobile device communicates with a selection of different sensor nodes to collect packets directly via short distance communications. However, this is not a solution appropriate for WirelessHART as a mobile sink is a physically moving device and is slow by packets transmission standards. The overall network cost will grow if several mobile sinks are deployed, and it is also challenging to maintain the schedules of such multiple sinks. Furthermore, WirelessHART networks are used in harsh environments such as oil fields and hence the mobile sink' solution is often totally impractical.

However, the use of unequal clustering algorithms [7] to alleviate the hotspot problem and enhance network performance may provide a more practical alternative for IWSN and future Industry 4.0 protocols.

In unequal clusters, cluster heads (CHs) remote from the gateway can have more members than those close to the gateway [7]. Considering that receiving and routing packets consumes large amounts of energy, distant CHs would not need to forward many packets and hence unequal clusters could result in more balanced energy consumption. This enhances bandwidth usage, reduces overhead, and improves network topology. This paper evaluates GR, based on two types of unequal clustering algorithms, the pre-set Density controlled Divide-and-Rule (DDR) [8] and the probabilistic Energy-Efficient Unequal Clustering (EEUC) [7]. To increase reliability, GR attempts to construct a graph where CHs have at least two CH neighbours to transmit packets to the gateway. We have compared GR based on unequal clustering algorithms and evaluated using energy consumption, Packet Delivery Ratio (PDR), throughput and average End-to-End Delay (EED) as performance metrics.

The rest of the paper is organised as follows. Section II gives an overview of GR in WirelessHART and unequal clustering algorithms. In section III the methodology of this paper is given. Our simulation setup and results analysis are presented in section IV. Finally, section V concludes the paper.

II. Literature Review

A. *Graph Routing in WirelessHART network*

There are several algorithms proposed for GR to improve the requirements of WirelessHART, ELHFR [9] is a commonly used algorithm that uses an uplink graph-routing mechanism based on the Received Signal Level (RSL) and uses the breadth first search (BFS) to select neighbours. When establishing links, ELHFR considers least-hop to be the only metric. The network-forming (NF) algorithm [10] adopts resource optimization strategies with GR for WirelessHART but has primarily considered reliability. AFC [11] constructed clustering based on WirelessHART topology for transmitting packets from sensor nodes to the gateway, its residual energy, communication load, and sensor nodes use energy consumption to determine which neighbours to use to transmit a message. The WirelessHART network still needs to be optimized by proposing load-balanced GR for sensor nodes close to the gateway to mitigate the hotspot problem. For achieving the requirements of industrial applications, GR is essential, and the present work bridges the gap to improve reliability performance of WirelessHART with balanced energy consumption.

B. *Unequal Clustering applied to routing*

By balancing energy usage, unequal clustering algorithms aid in overcoming the hotspot problem. These can be classified into three categories which are probabilistic, pre-set, and deterministic. In probabilistic approaches to CH selection, a probability is initially assigned to each sensor node which is utilised to determine CHs randomly or via a hybrid method. Their simplicity and low energy consumption make them popular. The deterministic approach is more effective and reliable than probabilistic approaches because the chosen CH is based on specific parameters such as residual energy, degree of the sensor node, and the gateway's distance. Pre-set approaches are not dynamic; prior to deployment in the physical world, the location of clusters or CHs is assigned [12]. Energy-Efficient Unequal Clustering [7] is a hybrid technique using unequal clustering. It divides the network into clusters of unequal size, and packets are transferred to the gateway using multi-hop routing. UCS [13] proposed an unequal clustering algorithm for cluster formation based on the distance between the source and the sink to the cluster formation is done. This results in 10–30 % better than an equal clustering algorithm. The energy-aware unequal clustering fuzzy algorithm described by EAUCF [14] uses fuzzy logic to produce a competition radius to reduce the number of cluster nodes closest to the gateway, thus reducing the number of packets transmitted. CHs are elected at random, and the radius of each CH competition is determined by the remaining energy and gateway distance. DDR presents static clustering of sensor nodes and optimal CHs selection in each round in order to solve unbalanced energy utilization that causes energy holes in the network [8].

To balance sensor nodes energy consumption and alleviate the network hotspot problem, this paper proposes applying unequal clustering algorithms on the topology of GR in a WirelessHART network.

III. Methodology

A. *Graph Routing Mechanisms in WirelessHART*

Graph Routing is widely used in WirelessHART network for packets communication to exploit a collection of all single-way paths connecting two sensor nodes. In general, a graph includes several paths and hence provides redundant routes to a destination. Since each sensor node has been connected to the network, the NM is responsible for configuring graphs and connection information [15]. The NM includes information about the network, such as all neighbours for each sensor node in the network and their signal levels, through regular sensor node reports [16]. Then the NM uses this information to configure several sub-graphs in the graph table, each of which has its unique graph ID. A node can have several sub-graphs passing through it, and it stores pieces of the sub-graph.

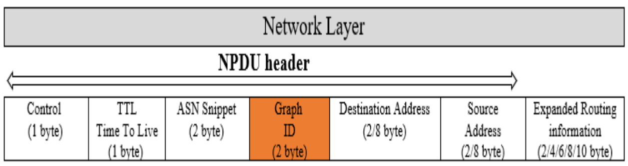
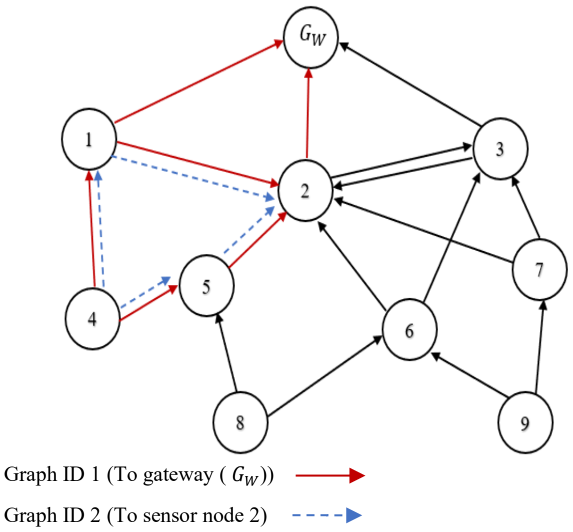


Fig. 1. WirelessHART NPDU structure.

After configuring the graph for the entire network and downloading the graph ID for each sensor node in the network, to send a packet between two sensor nodes, the source node writes a specific graph ID for the final destination in the header of the network layer protocol data unit (NPDU) [17] (see Fig. 1), according to table of the graph, which includes addresses of its neighbours and graph ID to route packets through the graph. No sensor node knows the entire route, and thus, until the packets reach their destination, they are transmitted through the pathway associated with the graph ID. In the other words, intermediate sensor nodes check the graph ID to find the neighbours, and selects the first link available for any of the neighbours to send the packet. The link in WirelessHART consist a number of the channels divided into time-slots, called '*superframe*', the link for each transmission between two sensor nodes is placed in the time slot in any superframe.

An example of the Uplink GR in mesh topology (UGR) strategy is illustrated in Fig. 2(a): red and blue arrows show the concept of UGR using Graph IDs for configured neighbours wherein sensor node 4 communicates with gateway (G_W) using (Graph ID = 1). Sensor node 4 may forward a packet to sensor nodes 1 or 5 in order to send it on that graph. From those sensor nodes, the packet may take several alternative routes, but it will eventually arrive at G_W if (Graph ID = 1) is followed. Similarly, sensor node 4 sends packets on (Graph ID = 2) to communicate with sensor node 2, , and it can forward the packets to several alternative routes through the intermediate nodes to reach to sensor node 2. As shown in Fig. 2(b), concept of superframe in WirelessHART which uses when designing routes by NM.



(a) Example of Uplink Graph Routing.

Timeslots / Ch. Offset	TS0	TS1	TS2	TS3	TS4	TS5	TS6
0	4 → 1			2 → GW	5 → 2		
1		4 → 5	5 → GW				
2	1 → GW					5 → GW	

→ Superframe N ←   → Superframe N+1 ←

(b) Example of links in superframe.

Fig. 2. Graph Routing, Concept Graph IDs and superframe.

B. Clustering Formation Phase

To balance energy consumption and simplify the GR path, the WirelessHART network topology applies the unequal cluster algorithms in two scenarios, based on DDR [8] and EEUC [7] algorithms. The primary and redundant paths between the CHs and the gateway are then generated where the normal nodes in the cluster communicate directly with its CH.

1) First scenario: WirelessHART DDR algorithm (WDDR): Fig. 3 is a flow chart that summarizes the clustering phase for the DDR algorithm with our improvement to be flexible with any WirelessHART network size. The initialization steps include:

- Determine the coordinates of the gateway (x_0, y_0) as "Center Point (CP)".
- Divide the entire area of the network (M ∗ M) into several levels of concentric squares.

The DDR algorithm used a fixed network size and fixed value of r (the distance between CP and the boundary of the first concentric square) (see Fig. 4) but in applying it with WirelessHART network, it will be calculated and derived as follows:

$$S = round\left({}^{M}/_{d_0}\right) \tag{1}$$

$$r = \frac{\left({}^{M}/_{2}\right)}{S} \tag{2}$$

Where S is the number of concentric squares and d_0 is the communication range. This is followed by dividing the area between every two concentric squares into rectangular areas as segments referred in [8]. Each segment will be considered a cluster, denoted as C (see Fig. 4). After cluster formation, CHs inside each one of these clusters are selected.

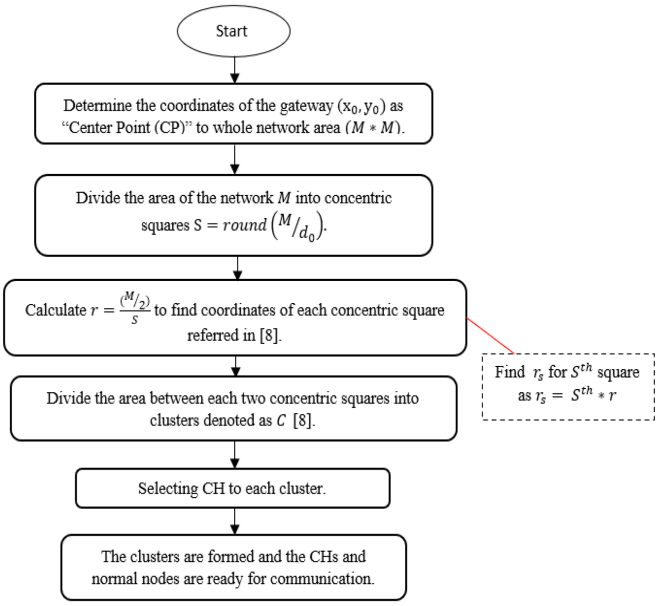


Fig. 3. Flow Chart of cluster phase in the WDDR algorithm.

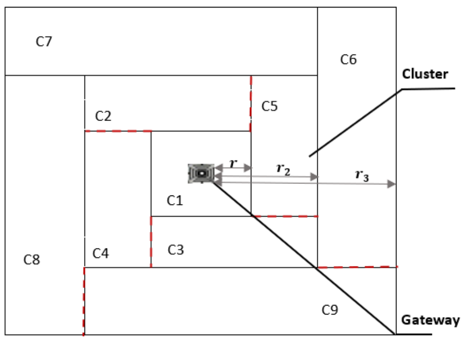


Fig. 4. Partitioning for the Area between two Adjacent Concentric Squares.

Based on Fig. 4, suppose that field of sensor nodes, is separated into three squares that are concentric, S = 3 and the concentric squares will be called Internal Square (S_1), Middle Square (S_2) and Outer Square (S_3). As shown below in (3), r_s will be a multiple of 2 for S_2 and a multiple of 3 for S_3 for concentric squares:

$$r_2 = 2 * r \quad , \quad r_3 = 3 * r \tag{3}$$

Hence, to find r_s is the distance between the gateway and boundary for any concentric square will be calculated as follows:

$$r_s = s^{th} * r \tag{4}$$

Where s^{th} is the ordinal number of a given concentric square.

- Cluster Head Selection in WDDR.

In WDDR, each cluster has its own CH, and the number of CHs remains constant during network operation. Sensor nodes will be connected to the nearest CH, regardless of whether CH is in the same cluster or another cluster to transmit their packets. This will reduce the communication distance.

The proposed technique is to perform the selection of the CHs based on the maximum residual energy rate between sensor nodes in the same cluster.

2) Second scenario (EEUC algorithm): The steps to apply the unequal clusters based on EEUC in WirelessHART topology are as follows:

First stage: Select tentative CHs randomly to compete for final CHs with probability T which is a predefined threshold:

a) Randomly, each sensor node generates a value from 0 to 1.

b) If the random value for the node is smaller than T, the node will be selected as a candidate CH; otherwise, other nodes go into sleeping mode until the CH selection stage ends.

c) Suppose CHs in the WirelessHART network can be expressed as: CHs= $\{h_1, h_2, h_3, \dots \dots, h_i\}$.

Second stage: Each tentative h_i needs to determine its own competition radius, which is a function of its distance to the gateway G_W. To control cluster size, it should be directly proportional to the distance to G_W. Following is the formula for competition range (5), R_{comp} [7]:

$$h_i.R_{comp} = \left(1 - b\,\frac{d_{max} - d(h_i - G_W)}{d_{max} - d_{min}}\right) R^0_{Comp} \qquad (5)$$

The maximum and minimum distances from the CHs in the WirelessHART network to G_W are represented by d_{max} and d_{min}, respectively. $d(h_i - G_W)$is the distance between h_i and G_W, R^0_{Comp} is the maximum value of the pre-defined competition radius, and b is a weighted factor with a value in the range [0,1].

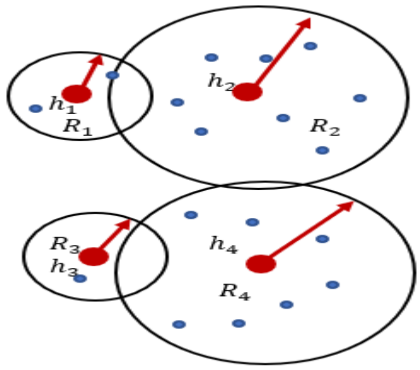


Fig. 5. The competition among tentative CHs.

As shown in Fig. 5, each tentative CH maintains a set CHs of its adjacent tentative CHs for select final CH from the same set based on the highest residual energy. Suppose h_i becomes a tentative CH, it has competition R_{comp}. If h_i is in h_j's competition diameter or h_j is in h_i's competition diameter, the tentative CH h_j is a neighbouring. The aim is to prevent the addition of a second CH h_j within h_i's competition diameter if h_i becomes a CH at the end of the competition [7].

C. Communication Phase

After the formation of unequal clustering in the WirelessHART topology, whether static or probabilistic, there are two phases to transmit data between sensor nodes and the gateway. The first phase is from each member sensor node in the cluster to its CH. In the second phase, GR builds a graph between CHs for transmitting data to the gateway by using multi-hop communication between CHs through the routing table. CHs may not be able to interact directly with the gateway because multi-hop communication may be required given restricted transmission range and battery power.

1) Intra-cluster routing (single hop): Intra-clustering communication refers to the transmission of sensor data from member nodes to their CH. In this algorithm, using direct communication with an active sensor node will transmit sensor data to its CH during the allocated time-slot on the superframe. If any node sends packet to the CH during its assigned time slot, all other nodes in that cluster remain asleep which leads to reduced energy dissipation and the intra-cluster collision that reduces the consumed battery of all member nodes.

2) Inter-cluster (multi-hop), build GR between CHs: In WirelessHART, the gateway is considered as the root node, ensuring that each CH has at least one hop path to the root node. The same mechanism of GR we mentioned it, but our GR algorithm depend on the remaining energy of each CH, two uplinks can be generated for it: a primary path and a redundant path. The redundancy paths of the network can prevent data loss caused by a node failure. The primary and redundant paths are generated between CHs as follows:

a) For the next hop, each source CH retains at least two upper neighbour CHs in the graph table. The source CH selects the neighbour CH with more remaining energy for the primary path; otherwise, it selects the different upper CH as the redundant path;

b) Proceed to step 1 if the next hop is not G_W; otherwise, the CH selects G_W as the primary path to transmit packet.

D. Energy Consumption model

In WirelessHART networks, data communication consumes a large amount of energy. We use an energy model that mainly calculates the energy consumed by a sensor node during data transmission. Based on the energy model in [7] the free space (d_0 power loss) model is utilised if the distance is less than a threshold between transmitter and receiver; otherwise, the fading multipath model (d^4 power loss) is used. The energy consumed for transmitting a K-bit packet over a distance d is as follows:

$$E_{Tx}(k,d) = \begin{cases} kE_{elec} + k_{\epsilon_{fs}} d^2, & d < d_0 \\ kE_{elec} + k_{\epsilon_{mp}} d^4, & d \geq d_0 \end{cases} \qquad (6)$$

The radio consumes energy in the process of receiving the following message:

$$E_{Rx}(k) = kE_{elec} \qquad (7)$$

Where E_{elec} is the consumed energy per bit to run the transceiver circuit, the energy loss factors in the hardware emission power amplification process are ϵ_{fs} and ϵ_{mp}, and the distance threshold is d_0. The energy consumption has a square relationship with the distance when the data transmission distance is less than to d_0; if the data transfer distance is higher than or equal to d_0, the energy consumption is four times that distance. This demonstrates that multi-hop communication is more effective in IWSNs.

IV. Simulation

A. Simulation Setup

Simulation for this research has been done in MATLAB R2021a, and a UGR in mesh topology model was developed for the WirelessHART network. The simulation parameters are presented in the table below and are similar to those used in the Section II related to GR algorithms of WirelessHART network and unequal clustering algorithms [7], [9]. The System model area has been assumed to be 100 x 100 m. The number of sensor nodes is initially 100 randomly distributed. Sensor nodes are stationary after deployment, and each sensor node is assigned a unique ID. For a WirelessHART network, the maximum packet size to be sent should be 133 bytes [3]. Every sensor node has a communication range of 35 meters [18]. Each node in a system is assumed to be homogeneous (i.e., all the same size and energy). The maximum energy of each node is assumed to be 0.5 J [7]. The energy model given in Section III has been implemented calculating, the energy consumed by each sensor node during the transmission of packets for each round where the number of rounds is equal to 50. The channel conditions are assumed to be static and do not change during transmission. In each round, the number of packets sent, received, and dropped and the energy consumption is calculated with a time-stamp. The performance of the UGR algorithm based on EEUC and WDDR is measured, and a comparison is conducted based on energy consumption, PDR, throughput, and average EED.

TABLE I. System Parameters.

Parameters	**Value**
Simulation area	100 × 100 m^2
Number of nodes	100
Nodes positions	Random
Number of rounds	50
Maximum Packet size	133 Bytes
Unequal clustering algorithms	EEUC and WDDR.
Routing algorithm	Uplink Graph Routing (UGR)
Communication range d_0	35 meters
Transmission power	0 dBm
Node initial energy E_0	0.5 J
E_{elec}	50 nJ/bit
E_{da}	5 nJ/bit/singal
ϵ_{fs}	0.01 nJ/bit/m^2
ϵ_{mp}	0.000013 nJ/bit/m^4

B. Results Analysis

1) Energy Consumption: This section assesses UGR's energy consumption. For this, as illustrated in Fig. 6, the three algorithms' total energy consumption is first compared. The sampling process involves 50 rounds of simulations, and the resulting graph indicates that the UGR with EEUC has considerably lower energy consumption than UGR in mesh topology and is similar to that of UGR with WDDR. As CHs oversee normal sensor node packets being sent to the gateway through a CH graph in both UGR with EEUC, and UGR with WDDR, every round saves significant energy.

2) Packet delivery ratio (PDR): As shown in Fig. 7, the PDR of UGR with EEUC is approximately 29% while that of UGR with WDDR is approximately 24% and that of simple UGR is 23%. However, UGR has a slightly lower PDR than other algorithms since more retransmissions which, in turn, leads to drops.

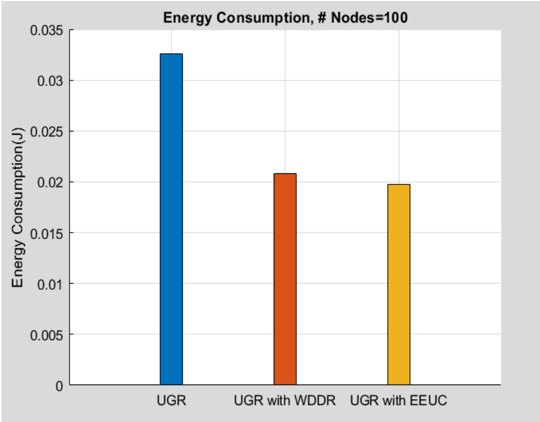


Fig. 6. Energy Consumption.

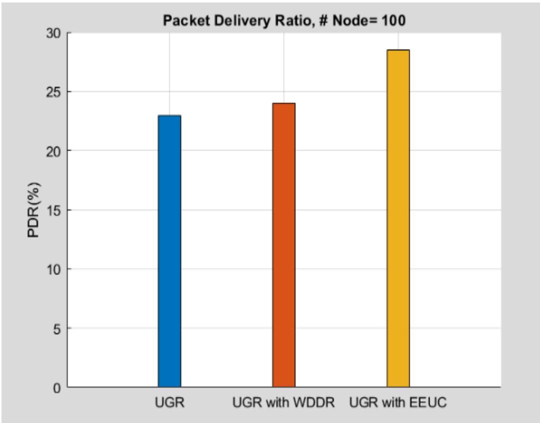


Fig. 7. Packet Delivery Ratio.

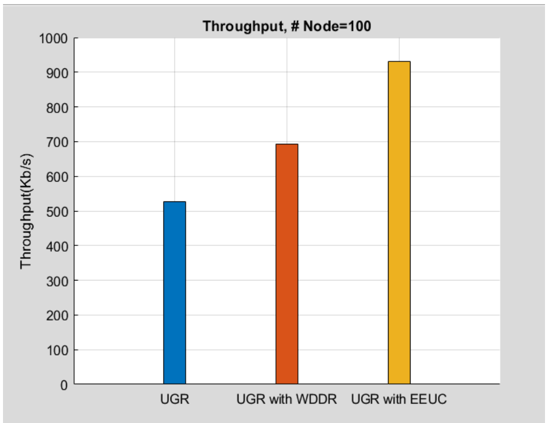


Fig. 8. Throughput.

3) Throughput: Throughput is one of the most important measurements of system performance. It is calculated by counting the total number of received packets at the gateway within a specified period of time. Because UGR with EEUC has less energy consumption, the number of dead nodes in a system is less, hence, it results in higher throughput than the other algorithms. UGR with EEUC provides a reliable path and routes the packets efficiently, which leads to the increase in the overall throughput of the network. The increment is throughput is mainly due to the reliable path to the gateway. The throughput of UGR, WDDR and EEUC as shown in Fig. 8 are 520, 700 and 925 Kbps respectively.

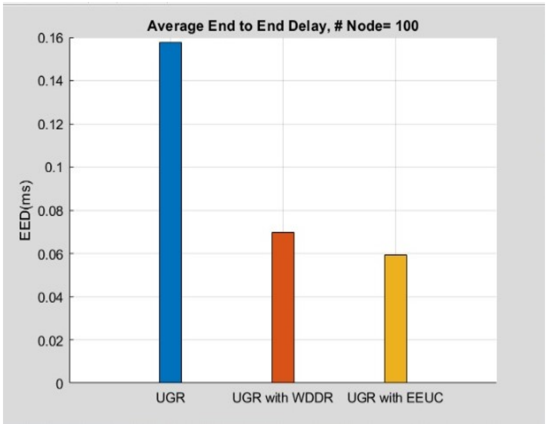


Fig. 9. Average End-to-End Delay.

4) Average End-to-End Delay (EED): As shown in Fig. 9, UGR with EEUC leads to reduced average EED to the network from WDDR and UGR with 0.06, 0.071, and 0.15 ms values. Fig. 6 and Fig. 7 indicate that the level of network connectivity using UGR is limited. The level of network connectivity improves considerably when using UGR with either WDDR or EEUC. Thus, the level of energy consumption and EED are considerably high using UGR without either WDDR or EEUC. Besides that, the throughput in Fig. 8 emphasizes the limitation of network connectivity when using UGR without WDDR or EEUC.

V. Conclusion

This paper examined how two types of unequal clustering algorithms (WDDR and EEUC) affect the performance of uplink graph routing UGR performance in WirelessHART networks, particularly with regard to the hotspot problem, examining energy consumption, throughput, average end-end delay (EED) and packet delivery ratio (PDR). It was observed that EEUC delivered better performance than WDDR for energy consumption, throughput, EED and PDR. Even though WDDR of static approach clustering, it delivers better results than UGR for all metrics considered here.

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