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A Collision Free Energy-Efficient Stochastic Routing Algorithm for Wireless Sensor Network

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Abstract - In the past decade, we have seen the enormous impact of mobile communication. The concept of mobile devices and wireless communication is being extended to unattended sensor nodes in a wireless sensor network (WSN) including the application in planetary exploration. In WSN, flat topology is simple and scalable, however, it is energy consuming compared to hierarchical architecture. Power draining due to relaying duplicates is the main drawback of flat topology. We propose a novel energy-efficient stochastic routing algorithm for flat topology in which each node chooses the next node for transmission that is closer to the destination. In this algorithm we are including a delayed relay in coordination with neighbouring nodes in the transmission range to minimize the redundant transmissions in flat topology. We use a stochastic function of distances to estimate the delay as routing parameter for deciding the next node on the path. In most normal cases the delay is zero. While energy depletion in a WSN node is unavoidable, our algorithm dynamically selects the available node for routing. Continuous transmission between distant nodes falters due to the lack of available routing nodes. Our algorithm optimally utilizes existing nodes for routing, resulting in an impressive 95.2% node utilization efficiency—an essential parameter for reliable routing. In a power constrained WSN environment lack of available routing nodes affects transmission between distant nodes. The proposed algorithm optimally utilizes alive nodes using collision free routing. Most energy-efficient routing algorithms for WSN are evaluated through simulations without visualisation. We have developed a Python-based interactive WSN Simulator and validated our algorithm through visualisation.

Index Terms – Energy-efficiency, Reliable, Dynamic, Routing, Wireless Sensor Network

I. INTRODUCTION

Wireless sensor networks (WSNs) have indeed gained significant attention and have started to make a considerable impact in various domains over the past two decades. WSNs consist of a large number of small, low-cost sensor nodes that are equipped with sensing, processing, and communication capabilities. These nodes collaborate to monitor physical or environmental conditions, collect data, and communicate wirelessly with each other or a central base station.

The emergence and proliferation of mobile communication devices have played a crucial role in the advancement and acceptance of WSNs. The concept of mobility, wireless communication, and the miniaturization of electronics have paved the way for extending the capabilities of WSNs to unattended sensor nodes.

In numerous industries and applications, WSNs have become just as vital as mobile devices. Industrial automation, infrastructure management, and agriculture have all benefited from their advancements. Additionally, fields such as healthcare, environmental monitoring and many more have been positively impacted.

In order to enhance decision-making, improve efficiency, and lower costs, WSNs can offer real-time information on the monitored environment by utilizing a significant quantity of sensor nodes. In WSN design and operation, one must consider the various constraints faced by sensor nodes. Some of the constraints that need to be considered are the limited power for direct communication and security, as well as the relay communication-related tasks and the lifetime of the operational network.

The battery power of a WSN node directly impacts its lifespan. In certain applications, it may not be practical to recharge nodes or replace batteries, so energy-efficient algorithms and techniques are used to prolong the operational life of sensor nodes. In certain situations, sensor nodes may need to act as intermediate relay nodes to facilitate communication between distant nodes and the base station. Optimization of energy consumption may necessitate the implementation of intelligent routing algorithms to select and establish intermediate relay nodes. Frequently, sensor nodes face constraints with their limited power resources that hinder them from transmitting data directly to the base station. To transmit data effectively and conserve energy, various techniques may be utilized, such as compression and aggregation of data, as well as the incorporation of relay nodes.

Wireless communication and the distributed nature of wireless sensor networks (WSNs) make them vulnerable to various security threats. Compromising sensor nodes can occur due to malicious attacks, tampering, and eavesdropping. WSNs maintain their security through the vital functions of data confidentiality, data integrity, and authentication.

In various fields, the impact of WSNs continues to increase, despite these constraints. They enhance automation and facilitate data-driven decision-making, providing valuable insights. The field of wireless sensing and communication has been revolutionized with the blending of WSNs and mobile communication, providing a plethora of fresh prospects for innovative applications and research advancements.

Akylidiz et al. [1] presented a wireless sensor network (WSN) scenario in Figure 1. In Figure 1, we show a number of static sensor nodes, deployed on planetary surface, a group of tethered nodes dropped inside a crater surface and a lunar rover acting as a mobile sink.

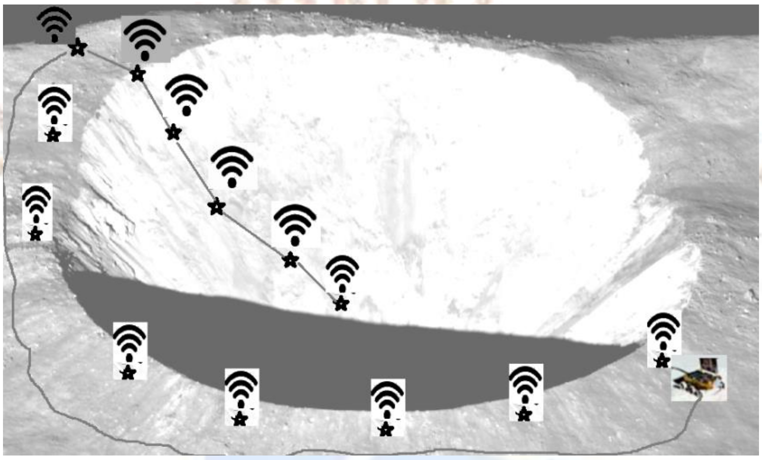

Figure 1: A typical planetary WSN scenario around a lunar crater with mobile rover sink and tethered sensor nodes

Transmitting the sensed and processed application-specific data wirelessly to other nodes within its transmission range is a capability that each sensor node possesses. Having computational capabilities and operating on constrained battery power, each sensor node also allows for data transmission.

As shown in Figure-2 (B) these sensor nodes are designed to be compact in size, allowing them to be seamlessly integrated into the network as long as a power source is available. In unattended environments, where battery replacement is unfeasible, the lifetime of the sensor nodes becomes an important factor to consider. By establishing communication and relaying data to the base station, multiple sensor nodes collaborate to form a wireless sensor network.

This network enables the collection and transfer of data from the sensor nodes to the designated sinks, facilitating further analysis and decision-making processes.

The composition of sensor nodes in a wireless sensor network is described in [1]. In Figure-2(A), we present a simplified block diagram illustrating a sensor node in a WSN. This node incorporates a low-power CMOS processor with a transceiver, switches and sensors. To operate, these modules are powered by either dry or rechargeable batteries. However, the performance of these devices is constrained by the transmission range (RF power) and the operational lifespan of the battery. Notably, the RF power is primarily influenced by the transmission activities, which consume a significant portion of the available power [1].

Furthermore, in Figure-2(B), we display a typical wireless sensor node within a wireless sensor network. This node comprises an ESP32 module for computation and communication purposes, along with 2 relay switches, an LM35 temperature sensor and 4 other optional sensor connectors. The power supply for these components is facilitated by a rechargeable lithium ion 5-volt battery. As with the previous scenario, the transmission range (RF power) and the operational life of the battery impose limitations on the functionality and longevity of these devices.

In Figure-2 (A) and (B), both cases, the components and configurations of the sensor nodes in a WSN reflect the trade-offs between power consumption, transmission capabilities, and the availability of suitable power sources. These considerations play a crucial role in ensuring the efficient operation and longevity of the wireless sensor nodes.

Many algorithms have been proposed for wireless ad-hoc networks. These algorithms are not suitable for unique characteristics and application specific requirements of wireless sensor networks due to dense deployment of WSN nodes, energy drained node fails, frequent change in the topology, broadcasting nature of transmission in WSN node, large number of nodes and less computing capability and storage compared to ad-hoc network nodes. [1]

Considering the aforementioned constraints in wireless sensor networks (WSNs), the dynamic optimisation of energy and network performance efficiency has emerged as a significant research focus. This issue involves identifying and analysing various parameters that can potentially enhance routing protocols, network topology, scheduling, and node architecture within WSNs. Parameters such as battery power, communication time, error rate, mobility, fault tolerance, and scalability are key considerations for potential improvements.

Among these parameters, energy efficiency and fault tolerance are crucial characteristics that often compete with each other. Techniques aimed at optimising energy consumption may inadvertently reduce fault tolerance, while achieving high fault tolerance levels may result in increased energy consumption. Krishnamachari et al. [10] have delved into this issue through analytical examples and simulations, shedding light on the trade-offs and challenges associated with balancing energy optimisation and fault tolerance in WSNs.

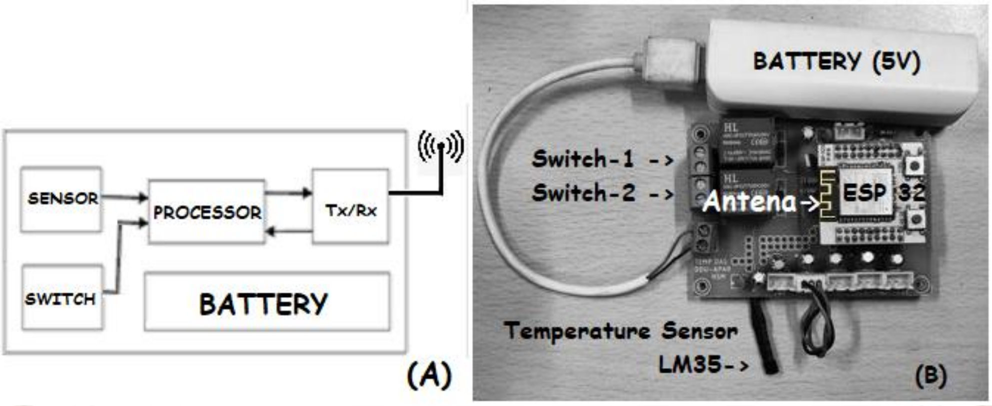

Figure 2: (A) A wireless sensor node block diagram (B) A wireless sensor node actual circuit board consist of an ESP-32 processor, LM35 temperature sensor inputs, and relay switch outputs used for ground testing prototype.

Efforts to optimise energy usage and enhance fault tolerance in WSNs are of paramount importance to ensure the longevity and reliability of the network. By exploring and developing innovative approaches, researchers aim to strike a balance between energy efficiency and fault tolerance, ultimately improving the overall performance and robustness of wireless sensor networks.

In the area of wireless sensor networks, researchers have explored various approaches to address the competing goals of improving network robustness and energy efficiency. Authors [10] have shown the inherent trade-off between these two areas. Other authors [19] have presented multicasting as a means to lessen network congestion. Their work reconstructs optimal multicast routing paths by considering the irregularity of the deployment area.

Another research group [2] have demonstrated the effectiveness of clustering as a method for reducing the amount of transmitted data, leading to improved reliability and energy consumption. By creating a hierarchical tree for inter-cluster and intra-cluster communication they achieve the goal. The work of Kyuhong and Heesang [11] shows the solution of node failures by incorporating backup nodes in the WSN. Their approach improves reliability in the event of potential breakdowns. Another work [16] has proposed an algorithm that utilises a specially designed routing tree, where each node has two parent nodes along the path to the sink. In their approach it enhances both the robustness and energy efficiency of the network. Jang Woon group [3] have presented an algorithm for increasing reliability in wireless sensor networks using k-disjoint paths. The number of disjoints paths are determined by the value of k, which is adjusted based on the occurrence of critical events.

These studies contribute to the advancement of wireless sensor networks by addressing the challenges of energy efficiency, robustness, reliability, congestion management, and data-centric approaches.

II. WIRELESS SENSOR NETWORK DESIGN IMPACT PARAMETERS

The following are important design parameters of wireless sensor networks:

(1) Fault tolerance: It ensures uninterrupted data transfer between nodes, even in the presence of relay sensor node failures by incorporating substantial number of redundant nodes (K) in the total number of nodes (N). Node Redundancy Ratio (NRR) is given by-

$$NRR = (N - K) / N \qquad (1)$$

Ensuring compatibility with high-density deployments is crucial when devising new routing schemes.

(2) Network Life: WSN life time can be extended using smart energy efficient stochastic routing algorithms. The network lifetime in a WSN can be modelled when choosing to relay a packet is done by a stochastic function of the remaining battery life. One way to model this is by using a probabilistic approach, where nodes make relay decisions based on their remaining energy levels. The network lifetime can then be calculated as the expected time until the first node in the network runs out of energy. Assuming that each node's remaining energy follows some probability distribution and that their relay decisions are independent of each other, we can calculate the node failure probability P_{nf} that at least one node runs out of energy within time t:

$$P_{nf}(t) = 1 - \prod_{i=1}^{N}(1 - P_i) \qquad (2)$$

Calculate the expected time until the first node failure $T_{nf.}$

$$T_{nf} = \int_0^{\infty} t \,.\, P_{nf}(t)\, dt \qquad (3)$$

The network lifetime T_{nlt} can be estimated as:

$$T_{nlt} = T_{nf} \qquad (4)$$

Here Pi is the probability that node i chooses to relay a packet based on its remaining energy and Ti is the time it takes for node i to run out of energy when it chooses to relay a packet. This approach assumes that Pi is a function of Ei as the remaining energy of node i and represents the probability of a node relaying a packet given its remaining energy. It also assumes that Ti represents the time it takes for a node to deplete its energy when it relays a packet. The specific forms of Pi and Ti would depend on the network's energy consumption model, and these functions would vary based on the network protocols and algorithms in use.

(3) Power Consumption: In battery operated sensor nodes, power consumption is an important parameter. Communication, data processing and sensing tasks are main components. Data communication typically incurs the highest energy expenditure [1].

$$P_c = N_T[P_T(T_{ON}+T_{ST})+P_{OUT}(T_{ON})]+N_R[P_R(R_{ON}+R_{ST})] \qquad (5)$$

where P_c is RF power, N_T/N_R are switching rate of transmitter or receiver, P_T/P_R are transmit or receive power, T_{ON}/R_{ON} are transmitter or receiver on time, T_{ST}/R_{ST} are transmitter or receiver start up time, P_{OUT} is output power of transmitter.

(4) The cost per sensor node: It is a crucial factor in achieving cost-effective solutions in WSN. Using redundant number of low cost low power nodes increases connectivity, reliability and overall cost of a WSN compared to traditional sensor networks [1].

(5) Network Topology: Topology maintenance plays a vital role in WSNs to address situations where nodes become inaccessible, unattended, or battery drainage. The hierarchical topology may not be preferred in certain applications like space exploration due to geographical constraints.

(6) Communication Range: RF communication is commonly used in sensor nodes due to its suitability for small packet sizes, low data rates, and efficient frequency re-use in short-range communications. This necessitates the use of low-duty-cycle radio electronics [1].

(7)Robustness: Sensor nodes are frequently deployed in remote geographic areas characterized by challenging environmental conditions. This highlights the importance of ensuring robustness and resilience in sensor networks [1].

III. ROUTING IN WIRELESS SENSOR NETWORK

Routing is a process implemented as network layer functionality in wireless sensor networks. It determines the path for transmission of data packets from source node to destination node. in a multi-hop network most of the source nodes do not have sufficient power to transmit the data packet directly to the sink. Routing protocols play a crucial role in the operation of energy-efficient WSNs because of their demonstrated effectiveness and adaptability [8].

Routing in a wireless sensor network (WSN) is one of the major challenges that need to be addressed, considering limited battery life, harsh environmental conditions, and the limited capabilities of sensor nodes. Many methods have been developed for sending data from a source node to a destination node using multi-hop communication in WSN [9,18 and15]. Routing protocols in WSNs can be classified based on network structure into four major categories: data-centric routing, hierarchical routing, geographical routing, and QoS-aware routing [15].

Data-centric routing protocols focus on the data itself rather than individual sensor nodes. Examples include Directed Diffusion [6] and SPIN [4], where data is named and propagated based on interest and diffusion techniques. Hierarchical routing protocols organise sensor nodes into a hierarchical structure, typically with cluster heads or a base station. Nodes communicate with their respective cluster heads, which aggregate and forward data to higher-level nodes. LEACH (Low-Energy Adaptive Clustering Hierarchy) is a well-known hierarchical routing protocol that forms to minimise energy dissipation [5].

Geographical routing protocols utilise location information to make forwarding decisions. Nodes exchange location information to determine the next hop based on proximity. Examples include GPSR (Greedy Perimeter Stateless Routing) and GEAR (Geographic and Energy-Aware Routing) [20, 7]. QoS-based routing protocols consider quality of service parameters, such as latency, reliability, and bandwidth, when making routing decisions. These protocols aim to satisfy specific application requirements. Examples include COQoS (Cross-Layer Optimisation for QoS) [17].

Most energy-efficient routing techniques rely on fixed static routing, which can lead to network shutdown if an event occurs between sensor nodes. Researchers aim to extend sensor node’s energy levels for longer durations [8].

Single-path routing is both time-efficient and scalable. It establishes a direct route between source and destination nodes within a specific time frame. Regardless of network size, whether it's ten nodes or a thousand, the complexity and path discovery process remain consistent [14].

One of the key components for power consumption is redundant transmission of same packet by several neighbouring nodes. The nodes are autonomous and works asynchronously with rules governed by the routing algorithms. The goal of efficient routing depends on (a) choice of the most appropriate relaying node and (b) avoid collision due to simultaneous transmission. The nodes in range can take a decision using the localized map and the packet destination to rank itself with respect to its neighbour. The rank can be converted to time slot to avoid collision. In this paper, we propose a dynamic, energy-efficient, and reliable single-path route based on above concept.

IV. PROPOSED COLLISION FREE ENERGY-EFFICIENT STOCHASTIC ROUTING ALGORITHM

The primary objective of the proposed routing Algorithm for wireless sensor networks (WSNs) is to minimise redundant transmissions, increase the routing efficiency and conserve the nodes' battery power.

(1) Assumptions

This Algorithm assumes the following conditions:

1. We assume a certain number of WSN nodes, say N, are placed randomly in a plain so that each node has at least a few, say M, neighbouring nodes within its transmitting range. Average number of neighbouring nodes M can be calculated as per following considerations.

   $$M = (N * \pi * R^2 / (L * W)) - 1 \qquad (6)$$

   Where N is total number of nodes in WSN area, R is range of transmission, L and W, are length and width of WSN area.

2. We assume that each node participates in a localization procedure using algorithm used in [12] at regular intervals to generate a list of all nodes N with their node-no and location information x and y using received signal strengths. Considering the received signal strength is inversely proportional to the square of the distance from the transmitting node. Given are the reference nodes (x1, y1), (x2, y2), and (x3, y3), and the distances d1, d2, and d3 from the unknown node (x, y) to these reference nodes. Table-1 shows the corresponding localization equations.

Table -1 Localization Equations

Equations of the differences in x and y coordinates between the reference nodes and the unknown node:		Equations using the distances and the differences in coordinates for the x-coordinate and the y-coordinate	
$\Delta x1 = x - x1$	$\Delta y1 = y - y1$	$(\Delta x1)^2 + (\Delta y1)^2 = d1^2$	$(\Delta x1)^2 + (\Delta y1)^2 = d1^2$
$\Delta x2 = x - x2$	$\Delta y2 = y - y2$	$(\Delta x2)^2 + (\Delta y2)^2 = d2^2$	$(\Delta x2)^2 + (\Delta y2)^2 = d2^2$
$\Delta x3 = x - x3$	$\Delta y3 = y - y3$	$(\Delta x3)^2 + (\Delta y3)^2 = d3^2$	$(\Delta x3)^2 + (\Delta y3)^2 = d3^2$
The above set of simultaneous equations for x and y coordinates are solved to localize all unknown nodes.			

3. We assume that WSN has required connectivity using Poisson distributed node density and transmission range.
   The connectivity can be estimated using probability mass function P(X=k). Minimum number of neighbouring nodes required within transmission range of a relaying node for reliable connectivity is estimated using equation-7,

   $$P(X=k) = e^{-\lambda} \lambda^k / k! \qquad (7)$$

   where X is the random variable representing the number of nodes in range at any instance, k is minimum number nodes desired for connectivity and λ is the average number of nodes in transmission range.

   We assume that any arbitrary node n1 sends a data packet to another arbitrary node n2. The node n2 returns an acknowledged packet back to n1. The packet headers are shown below.

Data packet:

pkt_seqno	n1	n2	nx	nh	typ=0	Data

Acknowledge packet:

pkt_seqno	n1	n2	nx	nh	typ=1

The packet headers shown above consist of a unique packet number ‘pkt_seqno’, source node number ‘n1’, destination node number ‘n2’, relay node number ‘nx’, hop count ‘nh’, and packet type ‘typ’. Here nh is incremented after every retransmission. Packet type ‘typ’ is set to 0 for data packets and 1 for acknowledge packets.

Upon receiving a packet, all nodes calculate a retransmission time slot based on their distance from the destination node. Each node then patiently awaits its designated time slot before transmitting the packet. Notably, the node closest to the destination generates the shortest delay compared to its neighbouring nodes. Once this node successfully sends the packet, all other nodes refrain from transmitting. This ensures only one transmission per hop.

(2) Algorithm

We consider a case of a data packet being transmitted from an arbitrary source node to another distant arbitrary destination node or base station. We assume the packet is sent with a unique packet number, a hop count and a packet type as 'TypFwd'. The packet is acknowledged with packet type as 'TypAck' and same packet number. The algorithm follows the following rules when a node receives a packet:

1. If the received packet's destination address matches the receiver node's address, the node promptly sends an acknowledgment packet back to the source node. The acknowledge packet retains the same packet number while setting the hop count to 0. Additionally, the source and destination addresses are swapped, and the packet type is marked as 'TypAck' from 'TypFwd'.
2. If the received packet's destination address differs from the receiver node's address, the node calculates a time delay as stochastic function of the distances to the destination node and residual battery power. This calculation relies on the pre-stored list of neighbors of the sender node and node distance table found in the localization table [12], which is regularly updated. During this delay, the node enters "Wait to Transmit = TRUE" mode and patiently awaits the expiration of the delay.
3. When sender receives the same packet being sent in step-3, it sends a short packet of packet type as 'TypRst' with same packet number to all its neighbors to set " Wait to Transmit = FALSE" to refrain from relay. This is done to inform those " Wait to Transmit = TRUE" nodes which are not in range of the relaying node of step-3.
4. While waiting for the delay period to elapse, the receiver node actively checks for any additional received packets. If a packet with the same packet number but an increased hop count or same packet number packet type marked as 'TypRst' is detected, the node changes the "Wait to Transmit" mode to FALSE.
5. If no packet with the same packet number is received during the waiting period, then the node computes the probability of transmission using a stochastic function of remaining power of its battery life as true or false. If the function outputs true, the receiver node proceeds to retransmit the packet with an incremented hop count (nh) and updates the relay node number (nx).

By adhering to these rules, the algorithm effectively minimises redundant retransmissions, thus conserving the nodes' battery power. Figure 3 in the provided example illustrates a packet route within a simulated WSN environment. The interactive visual simulation, developed exclusively for this research, is a dedicated Python project accessible through the corresponding GitHub repository [12,13].

(3) Algorithm Explained

In the example of figure-3 our WSN Python Simulator with 100 randomly placed nodes are shown. Node 2 and node 96 are arbitrarily selected as source and destination for routing a data packet. The algorithm shows energy-efficient route selection as described in the section-4. Node 2 sends the data packet to destination node 96 via relaying nodes 38, 43, 55 and 71. The destination node 96 returns an acknowledge packet to source node 2 via node path 92, 66, 49 and 29. Return path is different due to the hop optimizing conditions.

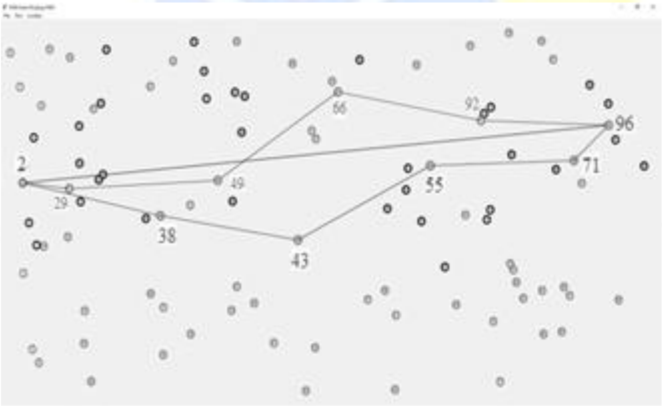

Figure 3: Data packet and acknowledgment packet transmission routes between an arbitrary pair of nodes (2, 96) are shown in our WSN Python Simulator.

In the example of figure-4, we consider a wireless sensor network (WSN), consisting of 100 nodes randomly deployed and numbered from 0 to 99. The source node is selected as node 14, and the destination node is node 89. A packet has just been retransmitted from intermediate node 42.

1. In the reception range of node 42, neighbor nodes are identified and marked within a big transmit range circle, as depicted in the figure.
2. Each neighbor node inside the range circle prepares to retransmit the packet after a designated delay. The delay is computed using the probability function of its distance from the destination node and remaining battery life. The delay is proportional to the distance, that means nodes closer to the destination will have shorter delays.

3. All nodes inside the circle are programmed to retransmit the packet after their respective delays if the packet has not already been transmitted by any other neighbor node.
4. Among the nodes inside the circle with enough battery life, node 63 has the shortest delay. Therefore, node 63 transmits the packet first, with additional reset packet from node 42. While all other nodes inside the circle receives the messages from 63 and/or 42 refrain from transmitting.
5. The circle then shifts its center to node 63 for the next hop towards the destination. This process continues until the packet reaches the destination node 89.
6. Once the packet reaches node 89, the algorithm repeats for the next hop from node 89 to node 2, this time with an acknowledgment packet.

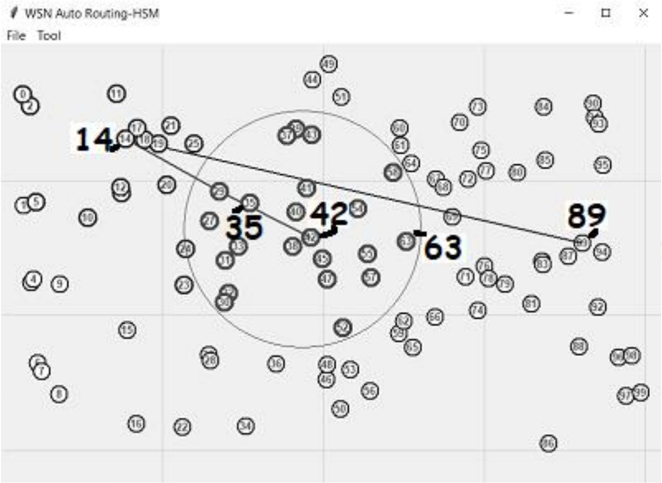

Figure 4: The operation of the proposed algorithm is shown after node 42 relays the packet from node 14 to node 89.

(4) Power Conservation

To conserve battery power in the wireless sensor network (WSN), the following measures are implemented:

1. Remaining Power Counter: A remaining power counter is used to simulate the battery usage of all nodes. The counter is initially set to 100, indicating a full battery. With each transmission, the counter is decremented accordingly.
2. Battery Level Monitoring: Each node continuously monitors its battery level. Once the battery level drops below a threshold, the node conserves power by refraining from transmitting any messages other than those intended for it. This feature is implemented in the stochastic function of battery life.
3. Visual Indication: Nodes with a remaining power counter below the threshold value are visually displayed in grey colour, as depicted in figures 5 and 6. This allows for easy identification of low-power nodes within the network.
4. Receive-only Mode: Nodes with a power level below the threshold still continue to receive broadcasted messages but do not retransmit them unless the incoming message is specifically addressed to the node itself. This helps conserve power by reducing unnecessary transmissions.
5. Low-Power Nodes: When a node's power level drops to 10 or below, it enters a sleep mode where it consumes very low power. These nodes are displayed in black colour. They only wake up periodically to send emergency assistance messages at predefined intervals.

By implementing these battery power conservation measures, the proposed algorithm ensures efficient usage of power resources within the WSN. Figure 6 illustrates the effectiveness of the Algorithm, even in extreme cases where most nodes in the network are at low power levels (shown in grey colour), as the Algorithm successfully finds a route using the few healthy nodes available.

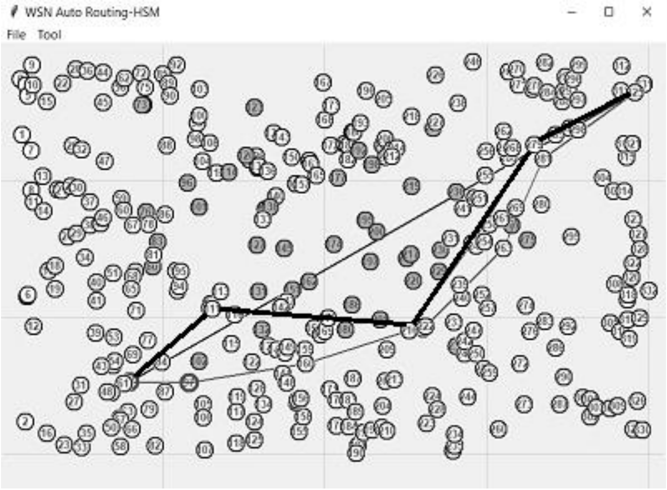

Figure 5 shows the data path in dark, thick lines and the acknowledgement path outside the data path in thin lines. The grey-shaded nodes indicate a low battery state and are unable to retransmit and allow the higher-delay nodes to participate in routing.

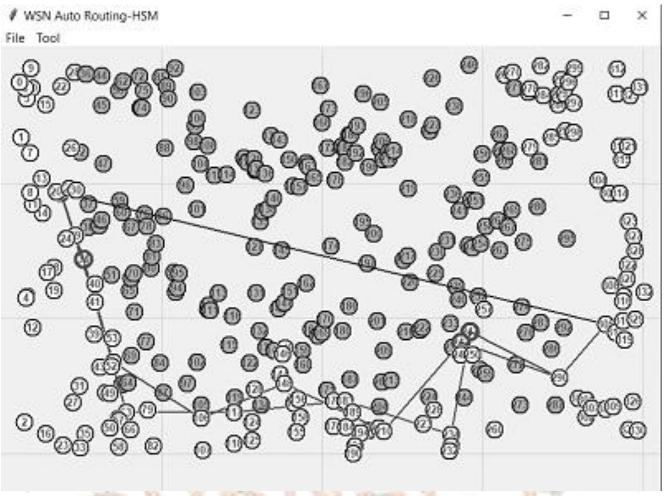

Figure 6 shows the instances where most of the nodes in grey shades are in a low battery state and have successful intelligent routing of data and acknowledge packets.

V. EXPERIMENTS AND ANALYSIS

(1) Transmitter Power vs. Number of Packets:

This study aims to investigate the impact of transmitter power on the total number of packets that can be transmitted on battery-powered nodes before they reach a critically low battery state. The experiment involves utilising a set of 300 randomly distributed nodes. Seven different transmitting ranges, representing various levels of transmitting power, are tested using the same set of nodes. It is important to note that higher transmitting power results in faster battery consumption. The experimental findings, as presented in Table 1 and illustrated in Figure 8, demonstrate an increase in the capacity for sending packets as the transmitting power of the nodes increases, despite the rapid draining of battery power. Additionally, in figure 7, we simulate [12,13] the repeated transmission of packets between two fixed nodes within the set of 300 randomly distributed nodes until the path becomes disrupted due to low battery issues. In our simulation, the battery drain for every packet transmitted is kept proportional to the selected hop range, which is linearly proportional to the transmit power.

Table-1 Hop Range Vs Packets for Battery Life.

Average Hops for Max Distance	Max Range Normalized for Average Hop	Total Packets for Battery Life
7	143	56
6	167	57
5	201	67
4	251	82
3	335	102
2	502	144
Range is proportional to the Transmit Power.		

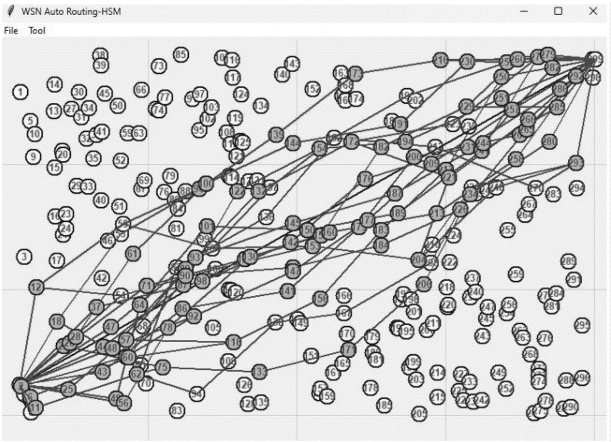

Figure 7. Screen shot of routes for 300 nodes with hop range 143. The grey nodes represent battery depleted state of nodes.

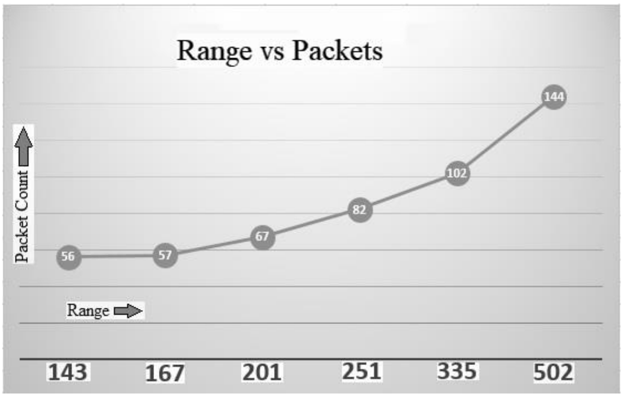

Figure 8 shows a plot of Maximum Hop Range vs. Total Packets transmitted for battery life. The experiments use 300 randomly distributed nodes with fixed source and destination nodes, as shown in Figure 7.

(2) Node Density vs. Number of Packets

In this research, we investigate the relationship between node density and the number of packets transmitted while considering battery life under a constant transmitter power setting. As we increase the node density, the available number of active nodes for relaying also rises, as evident from the data presented in Table 2 and illustrated in Figure 10.

Table-2 Node Density Vs Packets for Battery Life

Range for Average (4) Hopes	Total Number of Nodes	Total Packets for Battery Life
251	100	35
251	200	70
251	300	98
251	400	132

The experiment involved 100 nodes, and a screenshot of this setup can be observed in Figure 9. It is important to highlight that as the number of nodes increases, the volume of packets to be transmitted also grows correspondingly. However, what is noteworthy is that dense populations experience fewer unused nodes since continuous and uninterrupted communication is facilitated by the abundance of active nodes in close proximity.

Overall, these findings suggest that higher node densities lead to increased packet transmission, yet they also enable more efficient utilisation of nodes, resulting in fewer instances of unused nodes within the network.

(3) Transmitter Power vs. Routing Efficiency

In this study, we investigated the relationship between transmitter power and routing efficiency, specifically focusing on the count of unutilized nodes. Our experimental setup involved a routing simulation with 500 nodes between two fixed points, and we monitored the number of unused nodes when no viable routing path was available.

The outcomes of our experiment are summarised in Table 3, and the corresponding visualisation in Figure 12 illustrates the trend of routing efficiency concerning different transmit power levels. Notably, we observed a progressive increase in routing efficiency as the transmit range expanded, reaching a saturation point at higher power levels.

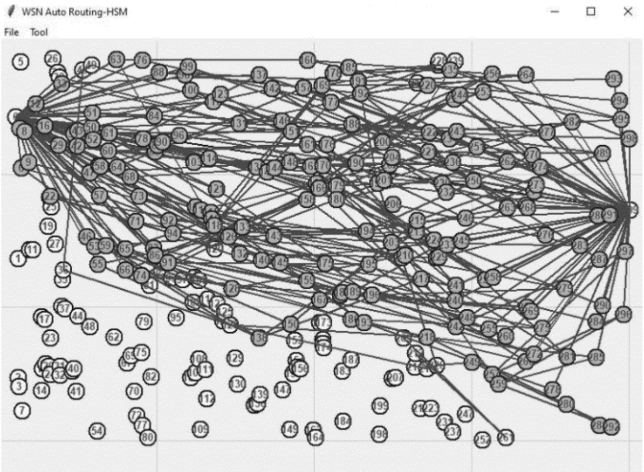

Figure-9: In this particular scenario, there were 300 nodes with a transmitting range of 251 normalised units. Out of these, 98 packets were successfully delivered with an acknowledgment. However, the transmission was hindered by the presence of low battery grey nodes, which prevented further communication.

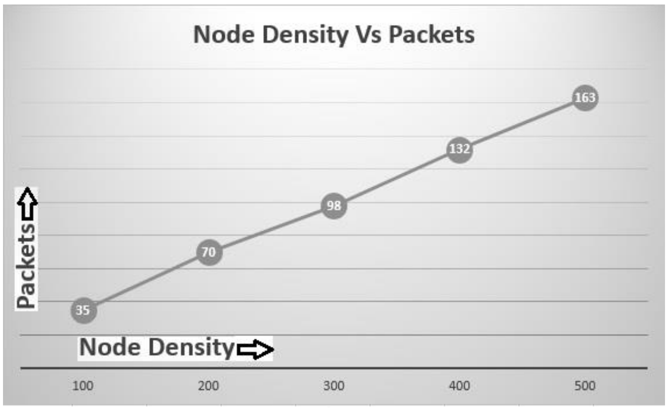

Figure 10 shows a plot of Node Density vs. Total Packets transmitted for battery life. The experiments use the results of Table 2 and show better energy efficiency at higher node densities.

Furthermore, in Figure 11, we represented nodes with low battery levels in grey, offering a visual perspective on their status within the network. Notably, a remarkable node utilisation efficiency of 95.2% was achieved when employing a transmission range set at 50% of the maximum distance between nodes. These findings indicate that optimising the transmit power within this range can significantly enhance routing efficiency and maximise node utilisation in the network.

Table-3 Transmit Power Vs Routing Efficiency

Range Normalized for Max Hop	Total Number of Nodes	Routing Efficiency In %
143	500	46.8
167	500	57.0
201	500	70.4
251	500	79.6
355	500	95.4
502	500	95.2

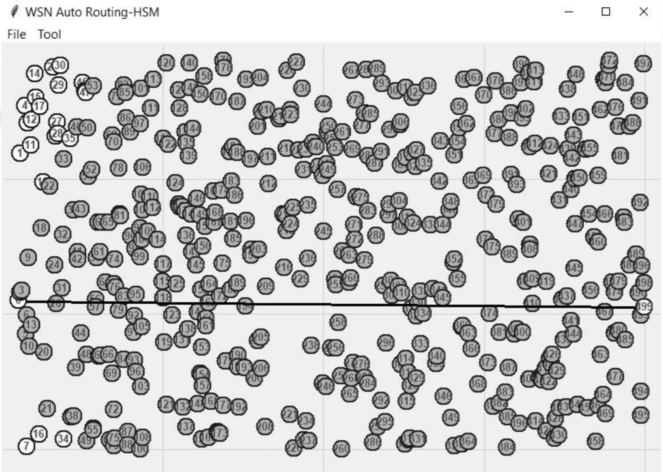

Figure 11: Nodes with low battery levels are represented in grey. A remarkable efficiency of 95.2% for a transmission range of 50% of the maximum distance between nodes is achieved.

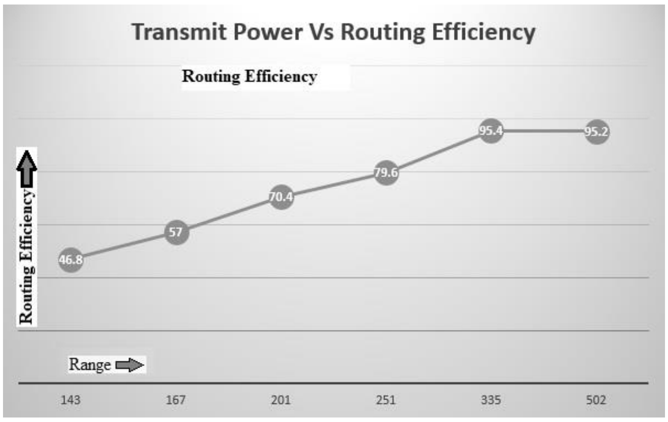

Figure 12: The plot of the result of Table 3 shows increasing routing efficiency with transmit range and levelling off at higher power.

(3) Transmission Range Vs Number of Nodes in Range

In this study, we investigated the relationship between transmission range and number of nodes in transmission range for different total number of nodes in WSN simulation. Result shows that increasing transmission range (power) do not help beyond a threshold value. The saturation is observed due to the range being extended beyond the WSN boundaries.

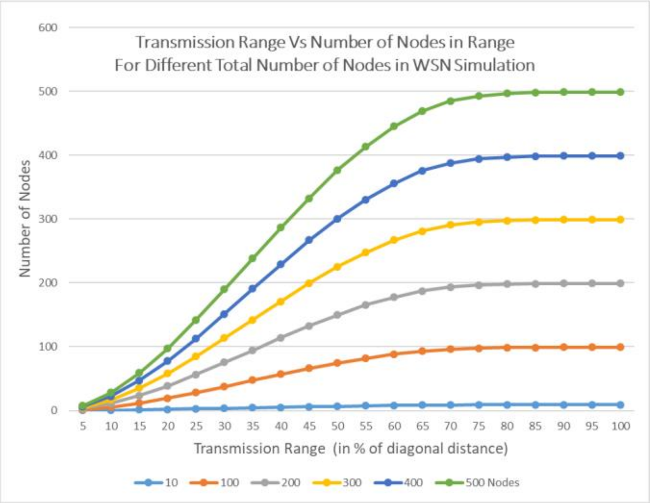

Figure 13: The plot of the transmission range vs number of nodes in range for different node densities.

VI. CONCLUSION

In conclusion, we have presented a novel energy-efficient and fault-tolerant routing algorithm for wireless sensor networks (WSNs) based on a weighted delay for re-transmission. By following a simple set of rules, each WSN node efficiently finds the optimum paths for packet transmission in multi-hop mode. The algorithm intelligently avoids sick or busy nodes by selecting alternate, efficient paths, ensuring reliable and efficient routing.

To validate the effectiveness of our proposed algorithm, we developed a dedicated Python-based visual WSN simulator. This simulator has been made available on Github [12, 13] for free utilisation by fellow researchers. By implementing the algorithm in various scenarios, we drew the following key conclusions:

The capacity for transmitting a higher number of packets increases with the transmission power while maintaining the same battery life. This finding emphasises the significance of optimising transmission power to maximise packet capacity.
The capacity for transmitting a higher number of packets also increases with node density while keeping the battery life constant. This highlights the importance of considering node density when designing WSNs to enhance packet capacity.

Our algorithm demonstrates automatic best alternative route-finding capabilities even in the presence of random dynamic failures of nodes. Our result shows 95.2% node utilisation efficiency using the proposed algorithm, which is an important parameter for robust routing. This fault tolerance feature ensures reliable packet delivery despite unpredictable node failures, enhancing the overall robustness of the WSN.

Overall, our proposed algorithm offers an efficient and fault-tolerant routing solution for WSNs, with demonstrated benefits in terms of increased packet capacity through optimized transmission power and node density. The availability of our WSN simulator on Github encourages further research and development in this field, fostering collaboration among researchers and facilitating the advancement of wireless sensor networks.

VII. DECLARATION OF GENERATIVE AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author(s) used Chat GPT in order to improve the readability of text only. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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