Mitigating the Event and Effect of Energy Holes in Multi-hop Wireless Sensor Networks Using an Ultra-Low Power Wake-Up Receiver and an Energy Scheduling Technique

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Abstract:
This research work presents an algorithm for extending network lifetime in multi-hop wireless sensor networks (WSN). WSNs face energy gap issues around sink nodes due to the transmission of large amounts of data through nearby sensor nodes. The limited power supply to the nodes limits the lifetime of the network, which makes energy efficiency crucial. Multi-hop communication has been proposed as an efficient strategy, but its power consumption remains a research challenge. In this study, an algorithm is developed to mitigate energy holes around the sink nodes by using a modified ultra-low-power wake-up receiver and an energy scheduling technique. Efficient power scheduling reduces the power consumption of the relay node, and when the residual power of the sensor node falls below a defined threshold, the power emitters charge the nodes to eliminate energy-hole problems. The modified wake-up receiver improves sensor sensitivity while staying within the micro-power budget. This study's simulations showed that the developed RF energy harvesting algorithm outperformed previous work, achieving a 30% improvement in average charged energy (AEC), a 0.41% improvement in average energy (AEH), an 8.39% improvement in the number of energy transmitters, an 8.59% improvement in throughput, and a 0.19 decrease in outage probability compared to the existing network lifetime enhancement of multi-hop wireless sensor networks by RF Energy Harvesting algorithm. Overall, the enhanced power efficiency technique significantly improves the performance of WSNs.

Keywords: Energy efficiency, Network Lifetime, Wireless Sensor Network

1. Introduction

Wireless sensor networks (WSN) have emerged as a promising technology for various applications, ranging from environmental monitoring to industrial automation [1]. WSNs are made up of tiny dispersed sensor nodes that are deployed to sense, process, and wirelessly transmit changes in the form of data from the environment they have been deployed [2,3]. However, the limited lifetime of the power supply of these nodes poses a significant challenge, as it directly affects the lifetime of the network. Because WSNs are often deployed in remote or inaccessible locations, manually replacing or recharging batteries is impractical. Therefore, energy efficiency becomes crucial to extend the operational life of the network [4, 5].

A key approach adopted in mitigating the energy efficiency problem in WSN is multi-hop communication. However, the process of transmitting substantial amounts of data through sensor nodes close to sink nodes often results in energy holes around the sink. Energy holes refer to areas where energy resources are depleted, causing reduced network performance and potentially disconnecting parts of the network [4,6]. As such, the need to mitigate the energy-hole problem and consequently improve the network lifetime of the WSN have become active areas of research. In mitigating the energy-hole problem, several approaches have been proposed and adopted to address the aforementioned challenges. Some of these approaches are mobile sink, transmission range control, a non-uniform node deployment technique, and energy provisioning [4].

Energy harvesting is the process of collecting energy from the environment (sun, wind) or other sources of energy (body heat, finger stroke, foot strikes) and converting these energies to electrical energy [2, 7]. RF energy harvesting and wireless power transfer are seen as a way of increasing the lifetime of WSNs. In RF energy harvesting, sensor nodes harvest energy from ambient RF sources; however, the availability of ambient energy sources is not always guaranteed. In wireless power transfer, the external energy sources are intentionally deployed in surroundings to extend the lifetime of WSNs [8].

In the context of this research, this work presents an improved network lifetime extension algorithm specifically designed for multi-hop WSNs. The objective of this research is to mitigate the effect of energy holes and improve the overall energy efficiency of the network. The algorithm proposed for this paper combines two key components: an energy scheduling technique and a modified ultra-low power wake-up receiver.

The energy scheduling technique focuses on reducing the power consumption in relay nodes, which play a crucial role in maintaining connectivity and data relaying in multi-hop WSNs. By optimizing the energy usage of these relay nodes, the proposed algorithm mitigates energy holes and ensures a more balanced distribution of energy resources across the network. Effective energy scheduling allows for the optimization of energy supply and demand, thus extending the lifetime of the network [9].

Additionally, the algorithm leverages a modified ultra-low power triggering receiver (WuRx) to improve the sensitivity of the sensor node while operating within a micro-power budget. The wake-up receiver serves as a key component in the energy-efficient design, allowing nodes to conserve energy during periods of inactivity and wake up only when necessary for data transmission or reception [9, 5]. The modified WuRx achieves a remarkable level of sensitivity, providing reliable communication while consuming minimal current in the power-limited environment of WSNs.

To evaluate the performance of the developed RF energy harvesting algorithm, extensive simulations are performed. The simulations consider various scenarios and network conditions to evaluate the effectiveness of the algorithm in mitigating energy holes and improving energy efficiency. Evaluation parameters include average energy charged, average energy harvested, number of energy transmitters, performance, and outage probability.

In summary, this work presents an improved network lifetime extension algorithm for multi-hop WSNs. This is achieved by addressing the challenges of energy holes and limited power supply, the proposed algorithm contributes to the overall enhancement of network performance and network lifetime. The algorithm incorporates a modified ultra-low power wake-up receiver and an energy scheduling technique to provide a practical solution to overcome energy inefficiencies in WSNs. The remaining sections of this paper are as follows: Section I discusses related literature. Section II delineates the materials and methods adopted in this work. Section III delineates the results obtained and discusses the implications of the results. Section IV concludes this paper.

I. REVIEW OF SIMILAR WORKS

This section provides a review of works that are relevant to this research area.

The work of [10] proposed mission-aware placement of RF-based power transmitters in wireless sensor networks. The author addressed the problem of optimal placement of RF power transmitters such that sensor nodes with replenished batteries take part in profit-maximizing missions. The batteries of the sensor nodes are refilled by a mobile wireless transmitter. An Integer Linear Programming (ILP) model, termed Mission-aware Placement of Wireless Power Transmitters (MAPIT), optimizes the positioning of RF-based transmitters in the Wireless Rechargeable Sensor Networks (WRSN) while maximizing the profit of the mission achieved. MAPIT optimized the placement of RF-based chargers in the WRSN such that sensors charged from a single landmark were maximized and they participated in profit-maximizing missions. Landmarks are the locations where wireless power transmitters park and transmit wireless power to the sensor nodes given that the distance between the transmitter and the receiver is less than the deployment cost. Wide coverage required the need for many transmitters, which made it necessary to use mobile transmitters. Simulations were carried out in terms of profit, under varying number of missions and a number of selected landmarks under varying numbers of landmark limits. It was shown that limiting the number of landmarks increases the profit because power transfer is made from less condensed locations. Meanwhile, profit reduced as the number of missions increased, because the nodes that took part in missions became geographically diverse and they were required to be charged from different landmark locations.

The work of [11] presented a Medium Access Control Protocol Design for sensors Powered by wireless energy transfer. The authors proposed a MAC protocol that works with RF energy harvesting termed RF-MAC that ensured optimal delivery to the requesting node. In RF-MAC, a node was expected to broadcast its Request For Energy (RFE) packet containing its ID and then wait to hear for Energy Transmitters (ETs) in the neighbourhood. Reponses from ET were called Cleared For Energy (CFE) pulses, which were simple, time-separated energy beacons. These pulses may be transmitted by more than one ET concurrently, as overlapping CFEs need not be distinguished. The concurrent emission of the CFEs increases the received energy level at the sensor, and this indicates a higher number of potential transmitters from the energy-requesting sensor. The responding ETs were then classified into two sets, based on rough estimates of their separation distance from the energy-requesting node to minimize the impact of destructive interference as much as possible. Each set of ETs was assigned a slightly different peak transmission frequency (separated by only a few KHz, hence still called in-band as the channel separation was typically 5MHz for 802.11) so that each set contributes constructively to the level of RF energy received at the node. Simulations were carried out to verify the effectiveness of the proposed MAC protocol using NS-2 and MICA 2 as the sensor nodes. It was observed that RF-MAC yielded over 89% and 112% more than the unslotted CSMA in terms of average harvested energy and average network throughput respectively.

The work of [12] envisaged a placement optimization of energy and information access points in wireless-powered communication networks. The authors considered the placement optimization of energy and information access points in wireless-powered communication networks (WPCNs), where the wireless devices (WDs) harvest the radio frequency energy transferred by dedicated energy nodes (ENs) in the downlink and use the harvested energy to transmit data to information access points (Aps) in the uplink. The authors were concerned about minimizing the network deployment cost with a minimum number of ENs and Aps by optimizing their locations while satisfying the energy harvesting and communication performance requirements of the WDs. The minimum-cost placement problem was first studied, where the

ENs and APs are uniquely positioned, where an alternating optimization method was proposed to jointly optimize the locations of ENs and APs. Then the placement optimization was studied, where each pair of EN and AP were co-located and integrated as a hybrid access point, and propose an efficient algorithm to solve this problem. Simulation results showed that the proposed methods can effectively reduce the network deployment cost and yet guarantee the given performance requirements, which is a key consideration in the future applications of WPCNs.

The work of [13] presented a wireless charger deployment optimization for wireless rechargeable sensor networks. This paper considered wireless chargers equipped with 3D beam-forming directional antennas and assumed they can be deployed on grid points at a fixed height to propose two greedy algorithms solving the following critical problem: how to deploy as few as possible chargers to make the WRSN sustainable. The first algorithm was the node-based greedy cone selecting (NB-GCS) algorithm trying to optimize the number of chargers based on node positions. The second algorithm was the pair-based greedy cone selecting (PB-GCS) algorithm trying to optimize the number of chargers based on node pairs. A simulation result was used to analyse the time complexity of the NB-GCS and PB-GCS algorithms. It was observed that the PB-GCS algorithms were better than the NB-GCS algorithms in terms of the number of chargers, while the former had lower time complexity.

The work of [14] proposed Wireless Sensor Networks with RF Energy Harvesting: Energy Models and Analysis. The authors commenced by considering the path-loss models between a transmitter and a receiver and estimating the power received between two nodes. Then. They went further to incorporate the results from array factor calculation in an N-element antenna array and phased array used to estimate the cumulative contribution of all the isotropic radiating elements at any far field point. The design factors of the hardware such as the diode operational parameters used in voltage multiplier sections of the energy harvesting circuit and RF-to-DC conversion efficiency were integrated into the proposed communication-centric analytical models. The emanating closed matrix expressions provide an estimate of the harvestable energy from multiple wireless ETs at any point, explicitly by considering the unique features of constructive and destructive combinations of RF waves. The authors formulated the location-dependent power harvesting rates in generalized 2D and 3D placement of multiple RF energy transmitters (ETs) for recharging the nodes of a WSN. The distribution of the total available and harvested power over the complete WSN was studied. Results obtained from the simulation showed that the received power from multiple ETs over the network and the network energy interference had log-normal distributions. It was further observed that the voltage harvested across the network has a Rayleigh distribution.

The work of [15] suggested an efficient tree-based power-saving scheme for wireless sensor networks with mobile sink. The authors presented a new tree-based power-saving technique for the reduction of energy consumption in wireless sensor networks using a mobile sink. A dynamic sorting algorithm is utilized in creating a tree-cluster routing structure for sensor nodes. The major idea behind the adopted technique was to minimize the data transmission distances of the sensor nodes by making use of a tree architecture and multi-hop idea. The proposed technique arrives at an energy-efficient decision for creating the routing structure, making use of the location of the mobile sink, the distances between the sensor nodes, and the residual energy of each sensor node. The use of the load balancing technique by the authors aids in reducing energy consumption and increasing the network lifetime of the sensor nodes. Simulation results showed that the proposed technique possesses a superior performance and can attain the required performance in terms of energy consumption, network lifetime, throughput, and transmission overhead. Additionally, suitable delay time and number of re-transmission messages can be achieved for the wireless sensor networks with mobile sink.

The work of [8] presented an Efficient Wireless Power Transfer in Software Defined Wireless Sensor Networks. The use of wireless power is a promising technology to replenish the sensor nodes. This involves the transfer of wireless power through dedicated energy transmitters. The authors presented an energy-efficient software-defined wireless sensor network (SDWSN) with wireless power transfer. A technique was created that can appropriately position the energy transmitters and determine the number of energy transmitters. A tradeoff between the maximum energy charged in the network and the fair distribution of energy was considered before energy transmitters could be appropriately placed. A mechanism was presented by defining a utility function to maximize both total energy charged and fairness to obtain the total number of energy transmitters involved in the formulation and solution of an optimization problem while satisfying the constraint on minimum energy charged by each sensor node. An energy-efficient scheduling scheme was formulated to schedule energy transmitters to undertake energy charging. The aim was to minimize the energy consumption of energy transmitters while ensuring that the sensor nodes were sufficiently charged. Simulation results showed how effective energy-efficient SDWSNs with wireless power transfer are in terms of energy charged, fairness, number of transmitters, number of tasks, and energy consumption.

The work of [16] suggested an Energy-efficient data sensing and routing in an unreliable energy-harvesting Wireless Sensor Network. The authors were concerned about making the right decision on the energy used for data sensing and transmission adaptively to maximize network utility and also about how to propagate all the accumulated data to the sink along energy-efficient paths to maximize the residual battery energy of nodes. The first procedure for solving this problem was by formulating a heuristic data sensing and routing problem. Then, unlike most existing work that focuses on energy-efficient data sensing and energy-efficient routing respectively, energy-efficient data sensing and routing scheme (EEDSRS) in unreliable energy-harvesting wireless sensor network was developed. EEDSRS takes account of not only the energy-efficient data sensing but also the energy-efficient routing. EEDSRS was divided into three steps: (1) an adaptive exponentially weighted moving average algorithm to estimate link quality. (2) a distributed energetic-sustainable data sensing rate allocation algorithm to allocate the energy for data sensing and routing. According to the allocated energy, the optimal data-sensing rate to maximize the network utility was obtained. (3) a geographic routing with unreliable link protocol to route all the collected data to the sink along energy-efficient paths. Finally, extensive simulations to evaluate the performance of the proposed EEDSRS were performed. The experimental results demonstrate that the proposed EEDSRS were very promising and efficient.

The work of [17] envisaged a sensor node scheduling algorithm for heterogeneous wireless sensor networks. The authors presented a scheduling algorithm for heterogeneous wireless sensor network to improve the regional coverage rate and network lifetime of heterogeneous wireless sensor networks. The author adopted an optimization model for regional coverage increment, arc coverage increments and residual energy. Multi-objective scheduling model is established using weight factors and integrated functions. Furthermore, the heuristic method was proposed to solve the multi-objective optimization model, and the scheduling scheme of heterogeneous sensor nodes was obtained. When the network is in operation for a period of time, some sensor nodes were invalid and relevant regions were uncovered. The repair method is proposed to wake up sleep sensor nodes and repair the coverage blind area. The simulation results showed that, keeping the same regional coverage rate, the sensor node scheduling algorithm improves network lifetime, increases the number of living sensor nodes, and keeps average node energy consumption at a low level.

The work of [4] offered a Network Lifetime Enhancement of Multi-Hop Wireless Sensor Network by RF Energy Harvesting. The authors sought to make the network more energy efficient by utilizing a multihop rather than a single-hop communication. When multiple amounts of data traffic are transmitted from the source node to the sink node, the problem of energy holes arises from nodes close to the sink nodes. The energy holes greatly affect the network lifetime of the sensor nodes. To alleviate the effect of energy holes, the author, presented an efficient RF energy harvesting using many dedicated RF sources to prevent energy holes. An ideal number of energy transmitters were optimally positioned in the network. The optimal placement of transmitters in the network guaranteed minimum energy among all sensor nodes but also delivered more energy for relay nodes to overcome their energy constraint which formed energy holes around the sink. The optimal number of energy transmitters was required to avoid energy holes in multihop WSNs. A utility function was defined for placing the energy transmitters, ensuring more weight for supplying energy to relay nodes and to maintain a minimum energy among all sensor nodes. For an optimum number of energy transmitters, an optimization problem is solved while satisfying the constraint on minimum energy charged by each sensor node. Simulation results were provided which illustrate the performance of multihop WSN with Wireless Energy Transfer in terms of energy charged, number of energy transmitters, throughput and outage in the network.

The work of [18] suggested an energy energy-efficient on-demand indoor localization platform based on wireless sensor networks using a low-power wake-up receiver: The authors presented an on-demand indoor localization platform using sensor nodes with built-in wakeup Receiver WuRx. The sensor nodes in the platform were kept in all–time WuRx idle listening and they consume only 3.7micro amp. Whenever they receive a wakeup packet (i.e. localization request), they become active and carry out the localization process. The approach has shown high energy efficiency by saving up to 90% of consumed energy compared to the duty–cycled approaches and the battery of the sensor nodes can reach a lifetime of 7.4 years within low-demand scenarios. The accuracy of the developed platform was tested by setting three anchors on the ceiling of an 80 ×80m2 room and the target was placed in 15 different positions inside it. The results obtained from the position estimations have shown a variation in the accuracy this came to the variation of the attenuation factor inside the room which is considered as a challenging environment. However, at high localization activity, the energy consumption of the anchor node increased in the WuRx-based ODIL. In such a situation, the lifetime of the network will not be prolonged.

The work of [19] presented a Lifetime Enhancement of WSN Based on Improved LEACH with Cluster Head Alternative Gateway. The authors maximized the network lifetime of the WSN by making use of another node to reduce the burden of the cluster head. This was achieved through the selection of an Alternative Gateway (AG) node on the cluster level by considering the residual energy and distance to the BS as input parameters in the AG selection process. The routing path selection process was refined by selecting a new node that has the highest residual energy in each cluster to be an alternative gateway for the cluster head. Then, the routing path will be decided based on distance. Thus, the traffic was channelled to the closest gateway for each node in the cluster, which eventually led to a prolonged network lifetime. This modified algorithm outperforms the original LEACH by a 4.35% increase in the residual energy, which prolongs the network lifetime. However, there was a slight increase in the overhead ratio.

From literature reviewed, the general challenge of insufficient energy in WSNs remains a major issue that needs to be addressed. The drawbacks as observed in most of literature reviewed, that is, 4, 10-17, delineated that the problems of energy holes in WSN have not been fully addressed. Nonetheless, the energy consumption by the energy transmitter can be effectively reduced by introducing task-based energy charging, where energy transmitters can be scheduled for wireless power transfer based on the charging demands of the sensor nodes. This helps to minimize the energy consumption of the energy transmitters. An Ultra-Low Power Wake-Up Receiver (WuRx) can also be used to reduce the energy consumption of the sensor node and to increase the sensor node's sensitivity.

II. MATERIALS AND METHODS

The following subsections provide a summary of the methodology used to improve energy efficiency and extend the Network Lifetime in a Multi-Hop WSN. Subsections A to J delve into the framework and methodology used in designing the simulation scenario to test the proposed algorithm. Subsection J also presents a flowchart illustrating the improved network lifetime extension in multi-hop WSN. Subsection K delineates the simulation setup for this work.

A. Division of Network into Number of Nodes

In this study, we examine a multihop Wireless Sensor Network (WSN) that incorporates RF energy transfer. The network consists of *Ns* sensor nodes denoted as $\left\{S_1, S_1.....S_{N_s}\right\}$. The sink is positioned at the centre and is constantly prepared for data aggregation. Among these sensor nodes, N_1 represents the number of nodes that act as relays. Additionally, the network includes N_e optimally placed energy transmitters denoted as $\left\{ET_1, ET_1.....ET_{NE}\right\}$.

Each sensor node has the capability to receive energy from all available energy transmitters. The maximum transmit power of an energy transmitter is denoted as *Pe*. It is assumed that all sensor nodes possess a single wireless interface, enabling them to switch between transmission and charging modes. The data transmission and energy charging process is illustrated in Fig. 1. The energy consumed by a sensor node within one time slot, is given in the work of [4].

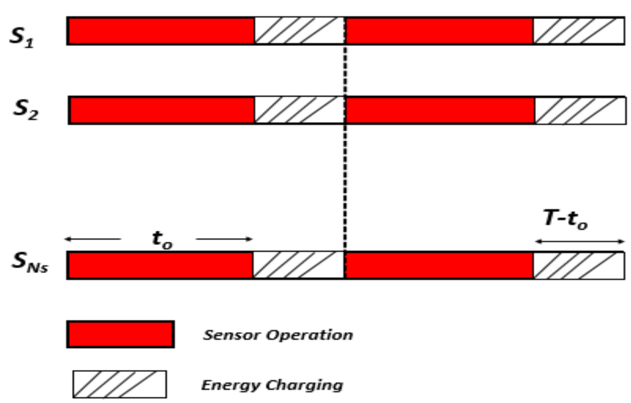

Fig. 1. Timeslot with Data Transmission and RF Energy Harvesting of Sensor Nodes

B. Energy Consumption Model

The energy consumed by the i^{-th} sensor node during data transmission was described using the radio model. Energy decay occurred at the transmitter side due to radio electronics and power amplification, while at the receiver side, it was solely due to radio electronics. A threshold distance, d_0, was defined. If the distance, *d*, between the transmitter and receiver, was less than d_0, the free space channel loss model, which was proportional to d^2, was applied as shown in the work of [4]. Otherwise, the multipath fading channel loss model, which was proportional to d^4, was used as shown in the work of [4]. The receiver-side loss was modelled according to (1).

$$E_{RXi} = E_{elec}\ x\ k \tag{1}$$

where:

E_{elec} is the transmitter circuitry dissipation per bit and *k* is the bit length.

Consequently, the overall energy consumption was determined.

C. Wireless Sensor Node Charging Model

Here, it was assumed that the energy transmitters were omnidirectional. The amount of energy charged by sensor nodes depended on the transmit power of the energy transmitter, the harvesting circuit, and the propagation properties of the environment. In a terrestrial environment, obstacles of various sizes cause reflection, refraction, and scattering of signals. As a result, the path loss in the terrestrial environment was higher than in the conventional free space path loss model. The developed model equation for the energy charged by the i^{th} sensor node when using an ultra-low power wake-up receiver in WSN can be represented as:

$$E_{c_i} = \left[\left(P_e - PL - \rho_i\right)\times\left(T - t_o\right)\right]\times\eta - \rho_r \tag{2}$$

Where:

E_{c_i} is the energy charged by the ith sensor node.

P_e stands for the maximum transmit power of the energy transmitter.

PL is the path loss in the environment.

ρ_i represents the power consumed in transmission by the i^{th} sensor node.

T is the total time available for energy charging.

t is the time spent on data transmission by the i^{th} sensor node.

η is the energy charging efficiency, which depends on the harvesting circuit.

ρ_r is the power consumed in reception by the i^{th} sensor node using ULPWuRx

D. Activating the Energy Scheduling Model by Setting Bode Transmission Threshold

The problems of energy holes in WSN have not been adequately addressed. The energy hole problem of the sensor node can be eliminated by adequate scheduling of the energy transmitters for charging the sensor nodes when they run out of energy. When the residual energy of the sensor node $\leq \theta_{th}$, the sensor node will be in the sleep state as shown in (3), while the energy transmitter is used to charge the sensor node equation in (2.6).In this study, the initial energy of nodes is 0.5 J. The Threshold energy level is set as 0.1 J [21].

$$E^*_{C_i} = \begin{cases} 0 & if \;\; E_R \leq \theta_{th} \\ 1 & if \;\; E_R > \theta_{th} \end{cases} \tag{3}$$

The threshold energy level is set as 0.1 J because of the following:

1. A choice of 0.1*J* is chosen to ensure that a reasonable amount of energy is always reserved in the nodes. By setting the threshold below the initial energy level of 0.5*J*, it allows for a buffer to account for energy fluctuations, noise, and potential energy consumption during transmission or processing.
2. The choice of 0.1*J* as the threshold energy level is based on ensuring the reliable operation of the nodes.

By setting a reasonably low threshold, it helps to avoid situations where nodes become completely drained of energy, which could lead to network failures, data loss, or compromised communication.

E. *Ultra Low Power Wake-up Receiver-based Placement of Energy Transmitters*

The main objective of the optimum placement of energy transmitters was to provide maximum energy to relay nodes and maintain a minimum energy level for all nodes. However, simultaneous optimization for maximum energy charging and energy distribution might not have always been possible. To avoid energy holes in multihop WSNs, we had to enhance the lifetime of relay nodes. Therefore, the placement of energy transmitters was done in such a way that they were positioned near the sink where energy hole areas existed. For the optimal placement of energy transmitters, a utility function as shown in [4] was modified to maximize the energy charged by relay nodes and maintain a minimum energy level among all nodes.

In the developed model, the utility function for the first energy transmitter with a wake-up receiver at position *(x, y)* depends on various factors, such as the distance from the transmitter, the energy received at different locations, and the wake-up receiver's performance characteristics. The utility function $U(x,y,d,E,P)$ is a combination of distance, energy, and wake-up receiver performance terms. The general mathematical presentation of the developed utility function is as follows:

$$U(x,y,d,E,P) = f(d) * g(E) * h(P) \tag{4}$$

Where:

(x, y) represents the position of the energy transmitter.

d represents the distance from the transmitter to a specific location.

E represents the energy received at that location.

P represents the wake-up receiver's performance, such as its sensitivity or probability of successful wake-up detection.

*f(d)*is a function that quantifies the impact of distance on utility

g(E) represents a function that quantifies the impact of energy received on utility

*h(P)*stands for a function that quantifies the impact of the wake-up receiver's performance on utility

The function *f(d)* quantifies the impact of distance on utility and can be an inverse function to represent diminishing usefulness as distance increases. The function *g(E)* quantifies the impact of energy received on utility and can be a monotonically increasing function that assigns higher utility values to higher energy levels received. The function *h(P)* quantifies the impact of the wake-up receiver's performance on utility and can be a function that assigns higher utility values to higher probabilities of successful wake-up detection.

F. *Analysis of the Number of Energy Transmitters*

The minimum number of energy transmitters was required to ensure that each sensor node could charge a minimum energy from a total of N_E energy transmitters. Finding this minimum number of energy transmitters was our next objective. By setting a low value for E_C, which was still sufficient for relay nodes, we could reduce the required number of energy transmitters. Mathematically, the problem of determining the minimum number of energy transmitters was formulated as follows:

$$E_{C_i - p} = h(P_i) \sum_{e=1}^{N_E} E_{C_{i,e}} \tag{5}$$

Where:

$h(P_i)$ are functions that quantify the impact of wake-up receiver performance, respectively.

$E_{C_{i,e}}$ Is the energy charged by node *i from* the energy transmitter

$E_{C_i,P}$ Stands for the required number of energy transmitters as a function of the WuRx sensitivity

N_E represents the minimum number of energy transmitters

G. *Analysing the Ultra-Low Power Wake-up Receiver*

Here, the model equation-based analysis of the existing ULPWuRx is carried out. The evaluation of the existing envelop detector of the power receiver is also examined in this study. Fig. 2 shows the schematic for ULPWuRx.

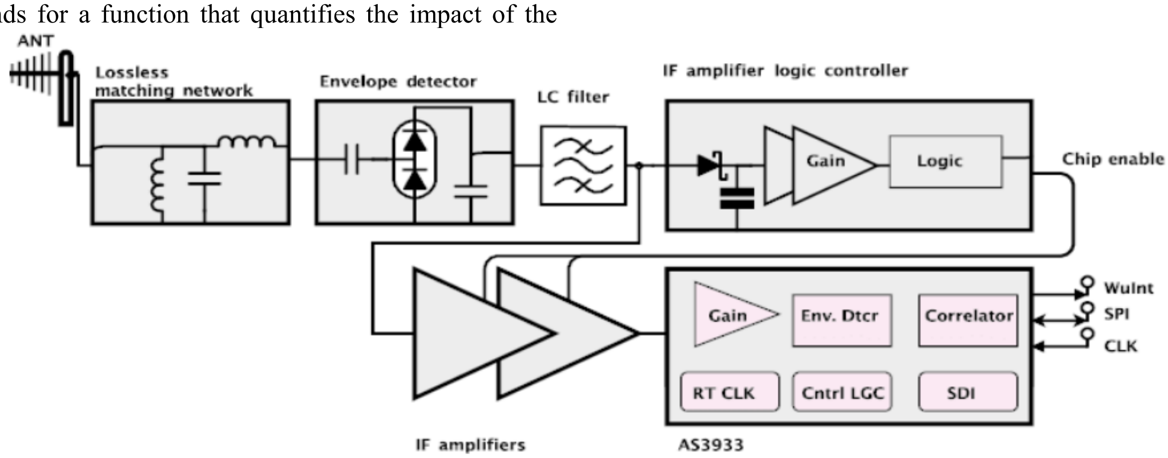

Fig. 2. Block Diagram of Wake-up Receiver [22].

1) Envelope Detector Circuit Equation

The envelope detector circuit is typically composed of a diode, a resistor, and a capacitor. Let the equation governing the behaviour of the envelope detector be represented as follows:

$$i_{env}(t) = i_{in}(t) - i_{out}(t) \quad (6)$$

where:

$i_{env}(t)$ is the current flowing through the capacitor of the envelope detector circuit.

$i_{in}(t)$ is the input current to the envelope detector.

$i_{out}(t)$ is the output current from the envelope detector.

2) Capacitor Voltage Analysis

The voltage across the capacitor in the envelope detector circuit can be described using (7):

$$v_{cap}(t) = \frac{1}{C * \int \left[i_{env}(t) \right] dt} \quad (7)$$

where:

$v_{cap}(t)$ is the voltage across the capacitor.

C is the capacitance value.

Also, the detection threshold determines the minimum voltage required for signal detection in the envelope detector. It can be expressed as [20]:

$$v_{th} = k + V_{dc} \quad (8)$$

where:

v_{th} is the detection threshold.

K is a constant related to the sensitivity of the envelope detector.

V_{dc} Stands for the DC bias voltage.

3) Sensitivity Analysis

The sensitivity of the envelope detector can be calculated based on the detection threshold and the input signal strength as discussed earlier. Let the sensitivity be given as:

$$S = \frac{P_{in}}{P_{th}} \quad (9)$$

where:

S Is the sensitivity.

P_{in} is the input signal power.

P_{th} is the power threshold for signal detection.

These equations provide a starting point for analyzing the behaviour of the existing Ultra-Low Power Wake-Up Receiver, particularly in relation to the capacitor configuration of the envelope detector circuit.

H. Modification of the Edge Envelop Detector Capacitor Configuration of the ULPWuRx

The configuration of the circuit components of the envelope detector has a significant impact on WuRx's overall performance. In order to accomplish the desired goals, components are therefore carefully chosen and configured in the circuit for better performance.

I. Capacitor-Based Modification of WuRx Envelop Detector

Notably. Comparators have been widely utilized in recently developed low-power Wake-Up Receiver (WuRx) circuits. To achieve high receiving sensitivity, the comparators used in WuRx circuits need to be highly sensitive to even slight voltage variations at their inputs. However, meeting this requirement often leads to design solutions that either consume excessive power or are highly susceptible to operational factors like temperature and power supply voltage.

High power consumption is undesirable in low-power WuRx designs, while extreme sensitivity to operational conditions necessitates complex calibration circuitry. In WuRx, comparators are employed to compare different voltage levels (input voltage versus reference voltage) or a voltage with a circuit design parameter (input voltage versus inverter threshold). This poses a significant design challenge for the comparators as both methods are highly susceptible to variations in manufacturing processes and operational conditions. Fig. 3 shows the edge envelop detector circuit from the work of [20].

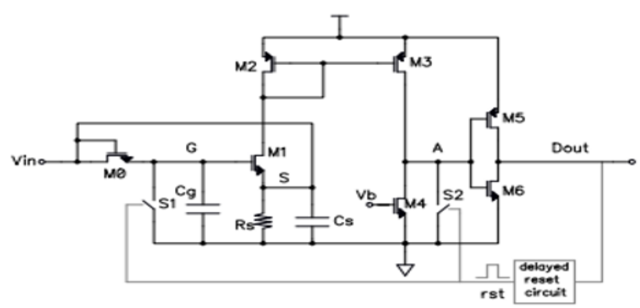

Fig. 3. Circuit Schematics of an Edge Envelop Detector

In this study, the configuration of the circuit components in the edge envelope detector was modified. Specifically, the connection of the capacitor was altered compared to the existing envelope detector design. This is shown in Fig. 4.

The equation for the capacitor-based modified envelope detector circuit can be expressed as:

$$i_{env-new}(t) = i_{in-new}(t) - i_{out-new}(t) \quad (10)$$

where:

$i_{env-new}(t)$ is the current flowing through the capacitor of the modified envelope detector circuit.

$i_{in-new}(t)$ stands for the input current to the envelope detector. $i_{out-new}(t)$ represents the output current from the envelope detector.

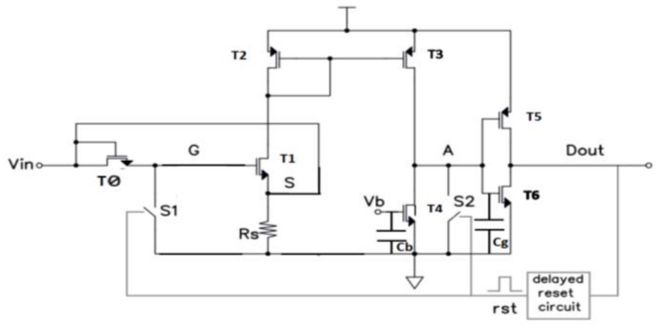

Fig. 4. Modified Circuit of an Edge Envelope Detector

1) Modified Capacitor Voltage Equation:

The voltage across the modified capacitor in the envelope detector circuit can be described by the equation:

$$v_{cap-new}(t) = \frac{1}{C * \int \left[i_{env-new}(t) \right] dt} \quad (11)$$

where:

$v_{cap-new}(t)$ is the voltage across the capacitor of the modified envelop detector.

C is the capacitance value.

The performance of the modified envelope detector was observed to be superior to the previous configuration

J. Incorporating the Ultra Low Power Wake-up Receiver with WSN

To incorporate both an energy scheduling technique and a wake-up receiver in a Wireless Sensor Network (WSN), the relevant equations and constraints from each aspect were combined. The developed model equation that demonstrates their incorporation is as follows:

Let x_i represent a binary decision variable indicating whether node *i* is active ($x_i = 1$) or inactive/sleeping ($x_i = 0$).

Let p^*_i represent the probability of successful wake-up detection for node *i*.

Let E_i represent the energy level of node *i*.

The model equation that shows the incorporation of the energy scheduling and Wake-Up Receiver is as follows:

$$x_i * P \le E_i \text{ for all nodes } i \quad (12)$$

This equation combines the energy scheduling technique and the wake-up receiver's behaviour. It states that the product of the binary decision variable x_i and the probability of successful wake-up detection p^*_i for node *i* must be less than or equal to the energy level E_i of that node.

In this formulation, if x_i is set to 1, indicating node *i* is active, the corresponding node can only consume energy up to its available energy level E_i. The wake-up receiver's probability of successful detection p^*_i contributes to determining the overall energy consumption capability of the node.

By incorporating this equation into the model, we can ensure that the energy scheduling technique controls the activation of nodes based on their energy levels and that the wake-up receiver's performance is considered in the energy consumption decision. This integration enables energy-efficient operation by selectively activating nodes based on available energy and successful wake-up detection, leading to enhanced network lifetime and efficient resource utilization. The flowchart that shows this incorporation is shown in Fig. 5.

K. Simulation Set-Up

Simulation of the developed RF energy harvesting algorithm was carried out using MATLAB 2017b. During the simulation, the network performance in terms of energy charged, number of energy transmitters, throughput and power outage was evaluated and compared with the work [4]. In the work, the nodes were randomly distributed in a rectangular area of 100 m × 100 m, ensuring a constant network density throughout the network area. The network was homogeneous, and all sensor nodes had a finite battery capacity. The nodes remained static and were equipped with a hybrid RF energy harvester circuit, allowing the harvested energy to be either immediately consumed or stored for future use. Additionally, the network lifetime of a multi-hop Wireless Sensor Network (WSN) was significantly improved by employing a modified Ultra-Low Power Wake-Up Receiver (WUR) in conjunction with an energy scheduling technique. The percentage improvement of the developed algorithm over the aforementioned works was evaluated using (13).

$$Percentage\ Improvement = \frac{\text{Developed Algorithm - } Existing}{Existing} \times 100 \quad (13)$$

Table 1 shows the simulation parameters of the developed algorithm.

TABLE I THE SIMULATION PARAMETER [4]

Parameter	Value
network size	100 * 100m
Sink location	(50, 50)
Number nodes	100
E_{elec}	50nj/bit
ε_{fs}	10pJ/bit/m4
ε_{amp}	0.0013pJ/bit/m^4
K	4000
Ω	4
p_e	46dbm
Frequency	2GHz
E_c	0.2J
η	70%
α	0.5
WuRx Sensitivity	-60dbm
Current in channel monitoring mode	2.53 µA
Energy harvesting	Enabled
Network topology	Multi-hop WSN

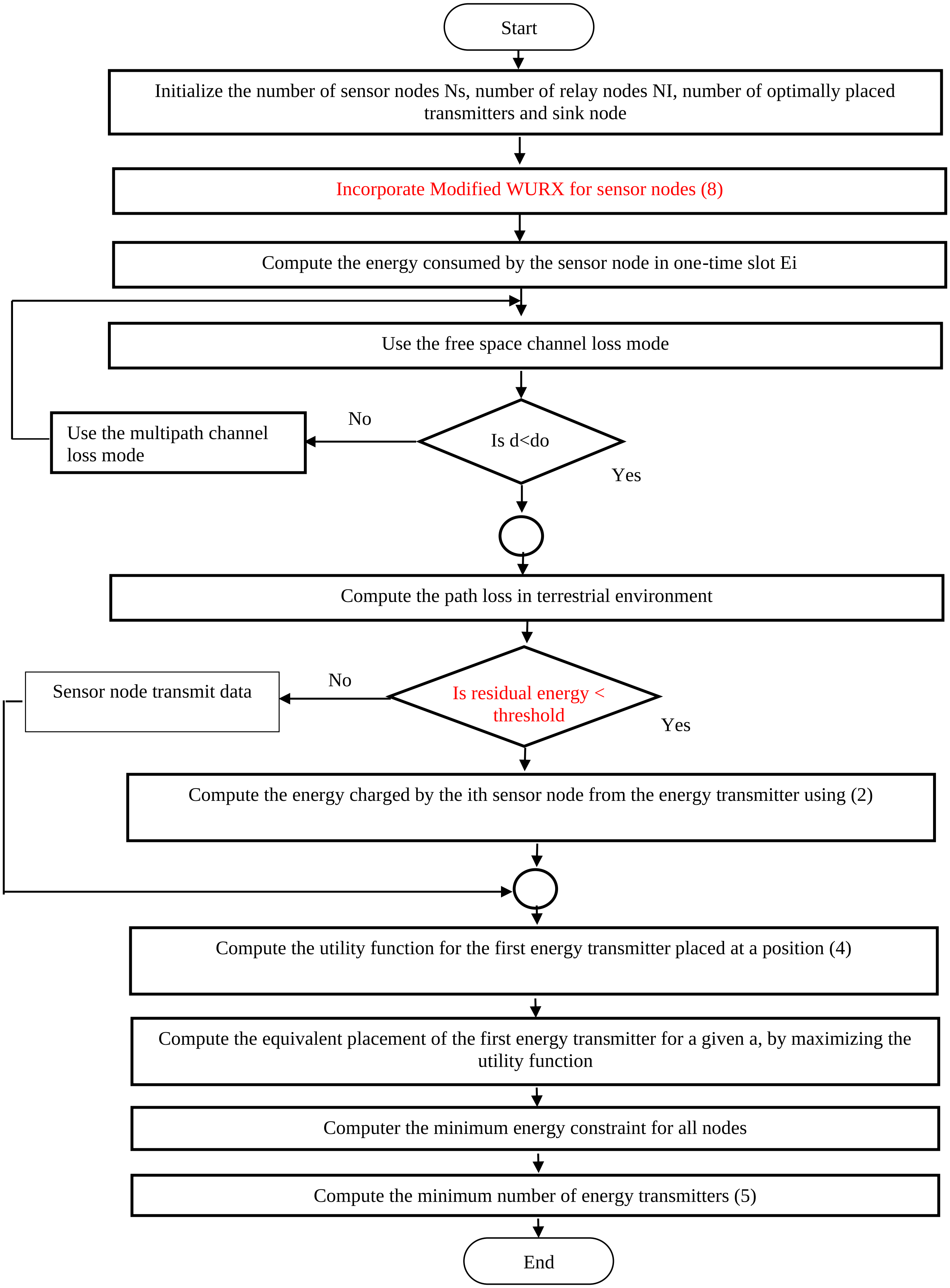

Fig. 5. Flowchart of the Improved Network Lifetime Extension in Multi-Hop WSN

III. RESULTS AND DISCUSSION

The simulation was carried out for the impact of a number of energy transmitters on average energy charge, minimum number of energy transmitters, outage probability and throughput as performance metrics to evaluate the performance of the improved lifetime enhancement of Multihop Wireless sensor Network WSN. The performance of the Lifetime enhancement of WSN of [4] and the developed system were compared.

Fig. 6 is a graph of the average energy charge against a number of energy transmitters for both the developed algorithm and the existing work. For a given minimum energy constraint, the average energy charged by sensor nodes as we place the energy transmitters optimally, till the required optimum number of energy transmitters is reached. It can be observed that for both the developed and the existing algorithms, as the number of energy transmitters in the vicinity increases, the energy charged by sensor nodes also increases.

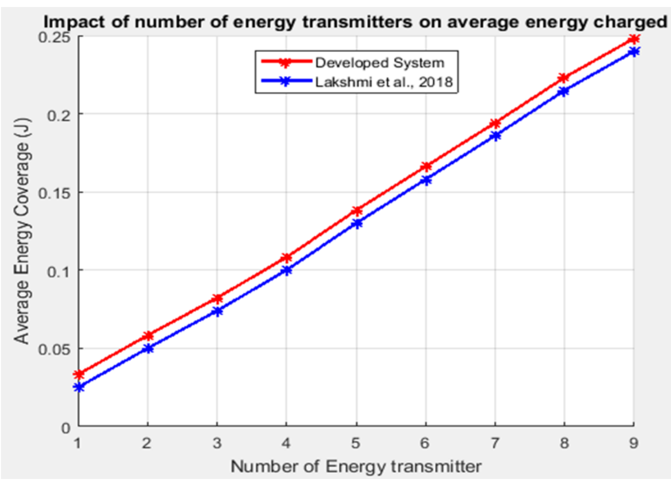

Fig. 6: Average Energy Coverage Against Number of Energy Transmitters

However, it can be observed that the developed algorithm outperformed the existing scheme with an average energy charge improvement of 7.69%. This is because the modified WUR improved the efficiency of energy harvesting from the surrounding environment.

It also increased the sensitivity to weak energy sources to capture and convert available energy more effectively. This enhanced efficiency allows for a higher average energy charged from the environment. Additionally, the modified WUR and energy scheduling technique minimized the energy losses within the network. By implementing energy-efficient protocols and algorithms, energy wastage due to idle listening, unnecessary transmissions, or excessive power consumption was reduced. This reduction in energy losses translated to a higher average energy charged by the WSN.

The modification that was carried out on the wake-up receiver, is in the modification of the envelop detector by altering the capacitor configuration which resulted in improved filtering characteristics and thus also led to a cleaner and more accurate envelope extraction. This cleaner and more accurate extraction resulted in better average energy charged. Table 4.1 shows the percentage improvement of the developed algorithm over the work of [4].

Fig. 6 is a graph of average energy harvested against the distance of nodes from the sink for both the developed algorithm and the existing work. Here, the energy distribution in the network after applying the developed algorithm is shown. It can be observed that for both algorithms, the average energy harvested decreases with an increase in node distance from the sink. This is because, as the node distance from the sink increases, the transmitted signal strength weakens over distance, requiring higher transmission power to maintain reliable communication.

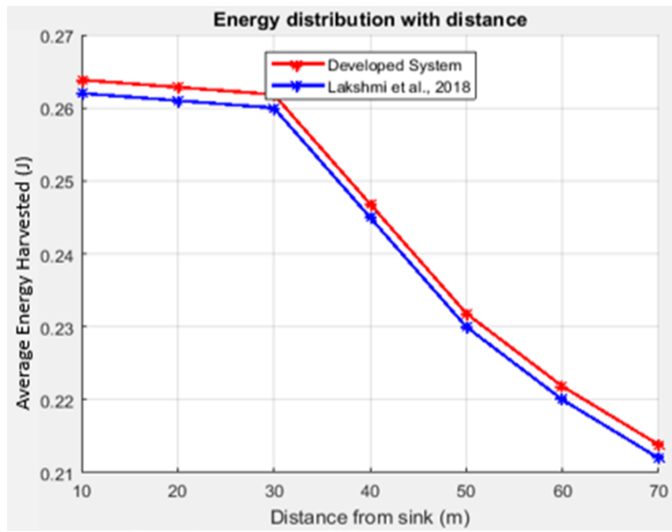

Fig. 7: Average Energy Harvested with Distance from Sink

The increased power consumption for transmitting data over longer distances leads to a higher energy expenditure, resulting in a decrease in the average energy harvested. Also, the longer distances can introduce more signal interference and noise in the communication channel.

However, it can be observed that the developed algorithm outperformed the existing work in terms of the energy harvested with a percentage improvement of 0.41%. This is because, the energy scheduling technique, combined with the modified WUR, enables optimized energy allocation across the network. By intelligently managing energy usage, allocating energy resources where they are most needed, and balancing the energy consumption among nodes, the overall average energy harvested by the WSN was increased. Also, the use of the modified WUR and energy scheduling technique led to an extended network lifetime. By conserving energy and ensuring more efficient utilization, the network operated for a longer duration before energy depletion. This longer operational time allows for a higher average energy harvested over the network's lifetime.

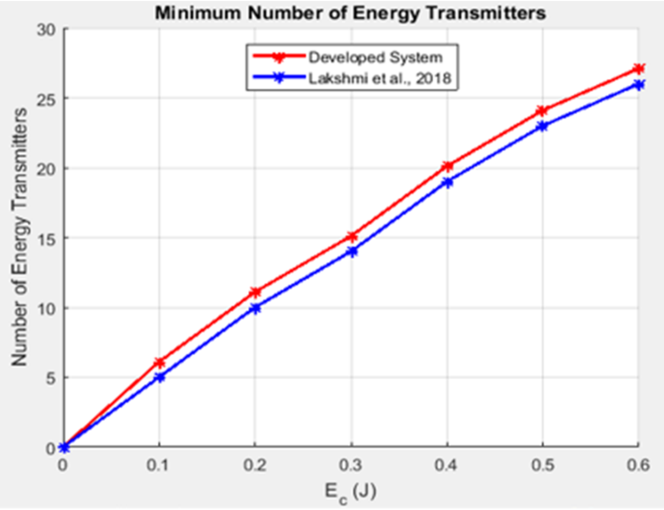

Fig. 8: Minimum Number of Energy Transmitters

Fig. 8 is a graph of number of energy transmitters against the minimum number of energy transmitters for both the developed algorithm and the existing work. Table 4.3 shows the percentage improvement analysis for the number of energy transmitters. In this analysis, each sensor node can charge minimum energy from the minimum number of energy transmitters. By setting a low value of minimum energy required, which is also sufficient for relay nodes then the required number of energy transmitters can be reduced. Also, the optimum number of energy transmitters required, in order to satisfy the constraints of minimum energy charged for 100 sensor nodes is shown in Fig. 8. It can be observed that as the minimum energy constraint for all nodes is increased, the required number of energy transmitters also increases. This is because, when the minimum energy constraint is raised, it implies that each node needs to have a higher energy level to operate effectively. As a result, more energy needs to be distributed throughout the network to meet the increased energy requirements of the nodes. This necessitates the deployment of additional energy transmitters to supply sufficient energy to a larger number of nodes.

Also, increasing the minimum energy constraint often requires extending the coverage area of the energy transmitters. The energy transmitters need to transmit power over longer distances or cover a larger geographic area to reach all nodes and provide the required energy levels. This expansion of the coverage area requires the deployment of more energy transmitters to ensure adequate energy supply throughout the network.

However, it can be seen that the number of energy transmitters for the developed algorithm exceeded that of the existing work by 8.39%. This is because when a modified ultra-low power activation receiver (WUR) and energy scheduling technique are employed, the network efficiently manages and distributes energy to the sensor nodes. This increased efficiency enabled a higher number of nodes to receive energy and meet their energy requirements. Consequently, it can be deduced that a larger number of energy transmitters may be necessary to adequately supply energy to the growing number of nodes. In addition, the modified Ultra-Low Power Wake-Up Receiver (WUR) and energy scheduling technique facilitated the scalability of the WSN by accommodating a greater number of nodes. As the minimum number of energy transmitters was raised, it indicated the need to support a larger network with more nodes. To ensure proper energy distribution and coverage across the expanded network, an increased number of energy transmitters becomes necessary.

Fig. 9 is a graph of throughput for both the developed algorithm and the existing work. Table 4.4 shows the percentage improvement analysis for the number of energy transmitters. It can be observed that the throughput increases with an increase I the number of rounds. This is because the enhanced placement of energy transmitters in multi-hop WSNs ensures that energy transmitters are correctly placed in the energy hole region. Since the transmitters supply enough energy for the relay nodes, their battery life will be enhanced and can function for a long time. Therefore, the number of packets delivered to the sink is considerably increased compared to the multihop network with an energy hole problem.

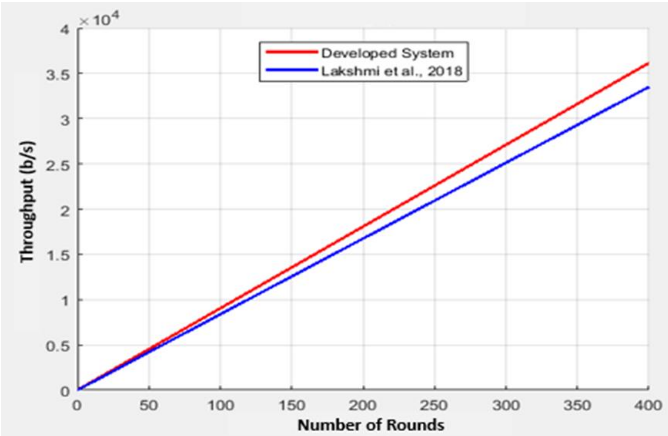

Fig. 9: Throughput against Number Rounds

However, it can be observed that the developed algorithm showed a better throughput improvement of 8.59% when compared to the existing work. This is because the modified Ultra-Low Power Wake-Up Receiver (WUR) and energy scheduling technique enhanced the energy utilization within the WSN. By efficiently managing and allocating energy resources, the technique ensured that nodes had sufficient energy to perform their tasks.

It can be deduced that this improved energy efficiency allows for more reliable and continuous operation of the network, resulting in higher throughput. Furthermore, the combination of the modified WUR and energy scheduling technique enabled better network coverage. With an increased number of rounds, more nodes were able to participate in data transmission and reception, leading to improved network connectivity and overall coverage. This expanded coverage allows for better data exchange, resulting in higher throughput.

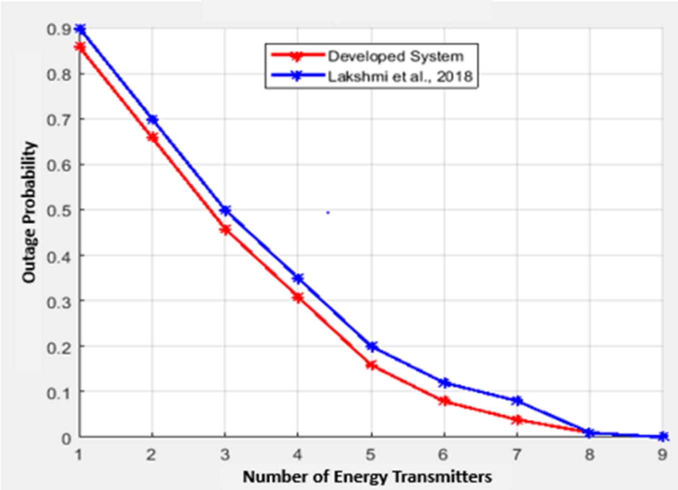

Fig. 10: Outage Probability against the Number of Energy Transmitters

Figure 4.5 is a graph of throughput for both the developed algorithm and the existing work. Table 4.5 shows the percentage improvement analysis for the number of energy transmitters. It can be observed that as the number of energy transmitters increased, the outage probability of the network also decreases. This is due to the fact that when a sensor node fails to harvest the minimum energy value from the deployed energy transmitters, it will experience an outage. So as the number of energy transmitters deployed for a given minimum energy value increases, the outage probability of the network also reduces. Every sensor node can successfully harvest the specified energy after a sufficient number of energy transmitters are optimally placed in the network.

It can be observed that the developed algorithm shows a lower outage probability as compared with the existing work by 0.19%, this is because the energy scheduling technique efficiently manages and allocates energy resources in the WSN. By optimizing energy usage and ensuring a balanced distribution of energy among the nodes, the technique helps to maintain sufficient energy levels for reliable operation. This improved energy management reduces the likelihood of energy depletion and subsequent outages, leading to a decrease in outage probability. Also, the modified WUR and energy scheduling technique enhanced the network connectivity by enabling more nodes to actively participate in data transmission and reception. As the number of rounds increases, the technique allows for better coordination and synchronization among the nodes, reducing the chances of packet loss or communication failures. This improved network connectivity contributes to a decrease in outage probability.

Deductions from the Modified Edge Envelop Detector Circuit

The performance of the modified envelope detector was observed to be superior to the previous configuration. This is because of the following:

The impact of the capacitors is to restore the fall time at the low time of the signal. So that the signal remains constant at a certain voltage level. Also, the transistors five and six in the edge envelope detector constitute a current booster, they amplify the low current signal that comes into the circuit.

1) Altering the capacitor configuration resulted in improved filtering characteristics, leading to a cleaner and more accurate envelope extraction.
2) By changing the capacitor configuration, the time constant was adjusted to better match the characteristics of the input signal, allowing for more efficient envelope tracking and detection.
3) By modifying the capacitor configuration, potential sources of distortion were mitigated, resulting in a more faithful representation of the original signal envelope.

The change in the capacitor connection within the edge envelope detector resulted in noticeable improvements in its performance metrics. The modified configuration showed greater efficiency and accuracy in capturing the envelope of the input signal. The envelope detection process became more reliable, allowing for more precise extraction of the varying amplitude of the modulated signal.

Comparative analysis between the modified edge envelope detector and the previous configuration revealed significant advantages. The improved detector demonstrated greater sensitivity, with the ability to detect even lower amplitude variations in the input signal. Furthermore, the modified configuration showed reduced noise interference, leading to clearer and more accurate envelope extraction.

The changes made to the component configuration of the edge envelope detector proved to be a crucial improvement, which had a positive impact on its overall performance. The superior performance of the modified design suggests its potential for applications that depend on accurate envelope detection, such as demodulation systems or signal processing techniques.

These findings highlight the importance of considering component configurations and design modifications in enhancing the performance of envelope detection circuits. The improved performance of the modified edge envelope detector opens up possibilities for more efficient and reliable signal processing in various fields, ultimately contributing to advancements in communication systems, wireless technologies, and related applications.

IV. Conclusion

Several researches have been carried out to improve the throughput, outage probability, number of energy transmitters and number of energies harvested for WSN. The significance of this research is seen in the improvement of user Quality of Service (QoS) using WSN in terms of throughput, outage probability, number of energy transmitters and number of energies harvested. WSN users will enjoy better coverage which ensures reduced transmission holes.

The contributions of this dissertation are as follows;

1) Development of an algorithm that mitigates the effect of energy holes in multi-hop WSN by RF energy harvesting using an ultra-low power wake-up receiver and an energy scheduling technique.
2) Results obtained from the simulation showed the following:
   i. The developed RF energy harvesting algorithm showed an Average Energy Charged (AEC) improvement of 30%

when compared with the work of [4].

ii. The developed RF energy harvesting algorithm showed an Average Energy Harvested (AEH) improvement of 0.41% when compared with the work of [4].

iii. The developed RF energy harvesting algorithm showed an improvement of 8.39% for the number of energy transmitters when compared with the work of [4].

iv. The developed RF energy harvesting algorithm showed a throughput improvement of 8.59% when compared with the work of [4].

The developed RF energy harvesting algorithm showed a throughput and outage probability decrement of 0.19 when compared with the work of [4].

For further extension of the study, the following are recommended:

Conduct a comprehensive scalability analysis to assess the performance of the WSN when the number of sensor nodes is significantly increased. Evaluate how the modified WUR and energy scheduling technique handle larger network sizes and if the improvements in throughput and outage probability are maintained. This analysis helps determine the scalability limits and potential areas for further optimization.

Explore additional methods to optimize energy efficiency within the WSN. Investigate advanced energy harvesting techniques, energy-aware routing protocols, or intelligent power management strategies that can further enhance energy utilization and prolong the network lifetime. Evaluate the impact of these techniques on the overall performance of the WSN, including throughput, outage probability, and the number of energy transmitters.

References

[1] S. Sarang, M. Drieberg, A. Awang, and R. Ahmad, "A QoS MAC protocol for prioritized data in energy harvesting wireless sensor networks," *Computer networks*, vol. 144, pp. 141-153, 2018.

[2] A. Rashid, F. Khan, T. Gul, S. Khan, and F. K. Khalil, "Improving Energy Conservation in Wireless Sensor Networks using Energy Harvesting System," *International Journal of Advanced Computer Science and Applications (IJACSA)*, vol. 9, pp. 354-361, 2018.

[3] M. Iyobhebhe, A. Adikpe, J. G. Bashayi, J. G., A. C. Akezi, I. C. Botson, E. Chukwudi, and O. B. Akinyele, "A Review on Dynamic Buffer Traffic Condition Protocol in Telemedicine." *Indonesian Journal of Computing, Engineering and Design (IJoCED)*, vol. *4, no.*2, pp. 15-24, 2022.

[4] P. S. Lakshmi, M. Jibukumar, and V. Neenu, "Network lifetime enhancement of multi-hop wireless sensor network by RF energy harvesting," Paper presented at the *2018 International Conference on Information Networking (ICOIN)*, pp. 738-743, 2018.

[5] F. C. Njoku, F. Ibikunle, and A. O. Adikpe, "A Review on Discontinuous Reception Mechanism as a Power Saving Approach for 5G User Equipments at Millimetre-Wave Frequencies," In *2023 International Conference on Science, Engineering and Business for Sustainable Development Goals (SEB-SDG)* (Vol. 1, pp. 1-7), April, 2023.

[6] D. K. Sah, S. Srivastava, R. Kumar, and T. Amgoth, "An energy efficient coverage aware algorithm in energy harvesting wireless sensor networks," *Wireless Networks*, vol. 29, no. 3, pp. 1175-1195, 2023.

[7] A. Singh, S. Redhu, B. Beferull-Lozano, and R. M. Hegde, "Network-aware RF-energy harvesting for designing energy efficient IoT networks," *Internet of Things*, vol. *22*, 100770, 2023.

[8] W. Ejaz, M. Naeem, M. Basharat, A. Anpalagan, and S. Kandeepan, "Efficient Wireless Power Transfer in Software-Defined Wireless Sensor Networks," *IEEE Sens. J.*, vol. 16, no. 20, pp. 7409–7420, Oct. 2016

[9] A. O. Adikpe, A. M. S. Tekanyi, and A. S. Yaro, "Mitigating the Signaling Resources Expended in 5G Location Management Procedures at Millimeter-Wave Frequencies," *Advances in Electrical and Electronic Engineering*, vol. 20, no. 4, pp. 572-583, 2023.

[10] M. Erol-Kantarci and H. T. Mouftah, "Missionaware placement of RF-based power transmitters in wireless sensor networks," in *2012 IEEE Symposium on Computers and Communications (ISCC)*, 2012, pp. 000012–000017.

[11] P. Nintanavongsa, M. Y. Naderi, and K. R. Chowdhury, "Medium access control protocol design for sensors powered by wireless energy transfer," in 2013 *Proceedings IEEE INFOCOM*, 2013, pp. 150–154

[12] S. Bi and R. Zhang, "Placement Optimization of Energy and Information Access Points in Wireless Powered Communication Networks," *IEEE Trans. Wirel. Commun*., vol. 15, no. 3, pp. 2351–2364, Mar. 2016

[13] J. H. Liao and J. R. Jiang, "Wireless Charger Deployment Optimization for Wireless Rechargeable Sensor Networks," in 2014 *7th International Conference on Ubi-Media Computing and Workshops*, 2014, pp. 160–164.

[14] M. Y. Naderi, P. Nintanavongsa, and K. R. Chowdhury, "RF-MAC: A Medium Access Control Protocol for Re-Chargeable Sensor Networks Powered by Wireless Energy Harvesting," *IEEE Trans. Wirel. Commun.*, vol. 13, no. 7, pp. 3926–3937, Jul. 2014.

[15] J.-Y. Chang and T.-H. Shen, "An Efficient TreeBased Power Saving Scheme for Wireless Sensor Networks With Mobile Sink," *IEEE Sens. J.*, vol.16, no. 20, pp. 7545–7557, Oct. 2016.

[16] T. Lu, G. Liu, and S. Chang, "Energy-efficient data sensing and routing in unreliable energy-harvesting wireless sensor network," *Wireless Networks*, vol. 24, no. 2, pp. 611-625, 2018.

[17] Z. Wang, Y. Chen, B. Liu, H. Yang, Z. Su, and Y. Zhu, "A sensor node scheduling algorithm for heterogeneous wireless sensor networks," *International Journal of Distributed Sensor Networks*, vol. 15, no. 1, 1550147719826311, 2019.

[18] G. Amir, D. Fauzi, F. Ghofrane, B. Sadok, B. J. Mahei, "Energy-efficient on-demand indoor Localization Platform based on Wireless Sensor Network using low power wake up receiver," *Elsevier*, pp. 1570-8705, 2019.

[19] A. N. Ateeq, I. Obaid, O. Othman, and A. Awad, "Lifetime enhancement of WSN based on improved LEACH with cluster head alternative gateway," In *Proceedings of the 4th International Conference on Future Networks and Distributed Systems* (pp. 1-6), Nov. 2020.

[20] Y. Wang, H. Wang, and G. Wen, "A novel envelope edge dedector for ultra low power wake-up circuit," In *international Symposium on Low Power Electronics and Design (ISLPED)* (pp. 371-376), Sept. 2013.

[21] M. Vellanki S. P. R. Kandukuri and A. Razaque, "Node Level Energy Efficiency Protocol for Internet of Things," *Department of Electronic Engineering and computer Science, Cleveland State University*, 3: 140, 2013.

[22] S. Bdiri, and F. Derbel, "An ultra-low power wake-up receiver for realtime constrained wireless sensor networks," Paper presented at the Proceedings of the *AMA Conferences, Nurenberg, Germany*, 2015.