LAUTECH Journal of Computing and Informatics (LAUJCI) – ISSN : 2714-4194
Volume 4. No.1, March 2024 – www.laujci.lautech.edu.ng

A Multi-level Effective Wireless Sensor Networks (WSNs) with Residue Number Systems and Intelligent Multi-Agent Technologies

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ABSTRACT

Wireless Sensor Networks (WSNs) consist of numerous sensor nodes spread across a targeted area, complemented by one or more base stations that monitor environmental and physical conditions. The primary challenges faced by WSNs include ensuring their energy efficiency, speed, and reliability. These networks operate on a limited energy reserve, complicating the process of energy replenishment. Additionally, the critical nature of the data collected from the environment demands that WSNs operate swiftly, reliably, and maintain functionality even in the event of component failures. Hence, designing WSNs to be reliable, energy-efficient, and fault-tolerant is crucial for enhancing their lifespan and overall performance. To address these challenges, the integration of the Residue Number System (RNS) and intelligent multi-agent technologies has been pursued to create WSNs that excel in fault tolerance, energy efficiency, speed, and reliability. Techniques such as the Chinese Remainder Theorem (CRT)-based packet division and the Low-Energy Adaptive Clustering Hierarchy (LEACH) algorithm have been developed to reduce energy consumption significantly. Additionally, the implementation of a High Spread REverse Converter (HISPREC) based on Mixed Radix Conversion for the moduli set $\{2^{n+1}-1, 2^n, 2^n-1\}$ facilitates the swift conversion of collected residues back into the original message by the Cluster Head (CH). Moreover, the adoption of intelligent multi-agent technology enables the WSN to monitor and control its operation dynamically, ensuring continuous operation even in the presence of faults and efficiently isolating any nodes compromised by power depletion. This design approach results in a multi-layered, efficient WSN framework that leverages the strengths of RNS and intelligent multi-agent technologies. This strategy is among the pioneering efforts to incorporate these technologies into real-time WSN applications, representing a significant advancement in the design and functionality of WSNs.

Keywords: Wireless Sensor Networks, Energy Efficient, Chinese Remainder Theorem, Packet Splitting, Cluster Head, Residue Number System, Moduli-set, Agent Technology

1. INTRODUCTION

Jindal (2018) describes wireless sensor networks (WSNs) as distributed networks comprising numerous sensor nodes scattered randomly. These nodes are endowed with computing, storage, and communication abilities, allowing them to function in challenging conditions and collect crucial data from their environment. Similarly, Khodabande, Toofani, Zarei, and Farzin (2013) detail that WSNs consist of spatially distributed, autonomous devices. These devices are equipped with sensors to monitor various physical and environmental parameters, such as temperature, sound, pressure, and wind direction. The collected data is then collaboratively transmitted across the network to a central base station or sink for further analysis, a process depicted in figure 1 of their work, and supported by subsequent studies (Barati, Movaghar & Sabaei, 2014; Sharma & Sharma, 2016). The potential for these devices to integrate closely with their environments has sparked considerable interest in WSN research over recent years (Attiah, 2018). Moreover, the sensor nodes tasked with event sensing and environmental data collection are typically characterized by their limited communication range, finite power supply, and low cost (Attiah, 2018). Given these constraints, particularly the limited energy resources which challenge the replacement or recharging of nodes post-deployment, the primary concern becomes managing and conserving energy to extend the network's operational lifespan. Consequently, designing applications for WSNs demands an approach focused on energy conservation (Lee, Min, Choi & Lee, 2016; Hamamreh, Haji & Qutob, 2018). Achieving energy efficiency often means optimizing the use of power to maintain service levels, thereby necessitating innovative strategies to prolong the life of energy-limited devices within the network (Attiah, 2018).

Fig. 1: A Typical Wireless Sensor Network (Kianifar, et al., 2015)

The universal truth that imperfection permeates everything implies that challenges are unavoidable in wireless sensor networks (WSNs), underscoring the importance of identifying operational versus malfunctioning nodes (Manisha & Nandal, 2015). Notably, WSN nodes are often deployed in vast numbers across remote and potentially hostile environments, predisposing them to higher failure rates compared to other network systems (Hamamreh, Haji, & Qutob, 2028). However, physically assessing sensor nodes for defects post-deployment is typically infeasible. This reality positions fault tolerance as a cornerstone for many WSN applications, which must maintain operational integrity in fluctuating and sometimes adverse conditions. Thus, the introduction of innovative technologies and diverse fault-tolerant strategies is crucial for enhancing the resilience and functionality of these networks (Jindal, 2018). Furthermore, embedding fault-tolerance features directly into the system architecture and prioritizing fault-prevention can significantly bolster the reliability of WSNs.

Considering the design and operational dynamics of WSNs, it becomes imperative to forge solutions that are energy-efficient, swift, reliable, and capable of withstanding failures (Hamamreh, Haji, & Qutob, 2018). This endeavor led to the integration of the Residue Number System (RNS) and intelligent multi-agent technologies in developing proficient WSNs. RNS is strategically utilized to streamline data aggregation and processing, enhancing speed, reliability, and network longevity. Simultaneously, the application of intelligent multi-agent technology furnishes the network with robust fault tolerance, ensuring that WSNs can navigate and adapt to challenges effectively.

2. LITERATURE REVIEW

In real-time Wireless Sensor Networks (WSNs), various strategies have been employed to enhance energy conservation while ensuring rapid operations. A landmark in the development of energy-saving techniques for WSNs is the introduction of the Low Energy Adaptive Clustering Hierarchy (LEACH) algorithm. Proposed by Heinzelman, Chandrakasan, and Balakrishnan in 2000 and further discussed by Hamamreh, Haji, and Qutob in 2018, LEACH represents the first and one of the most effective hierarchical clustering algorithms aimed at minimizing power consumption within WSNs. This algorithm, illustrated in figure 2, revolutionized the approach to energy efficiency in WSNs by dynamically organizing the network into clusters and rotating the role of cluster heads to distribute energy usage evenly across the network.

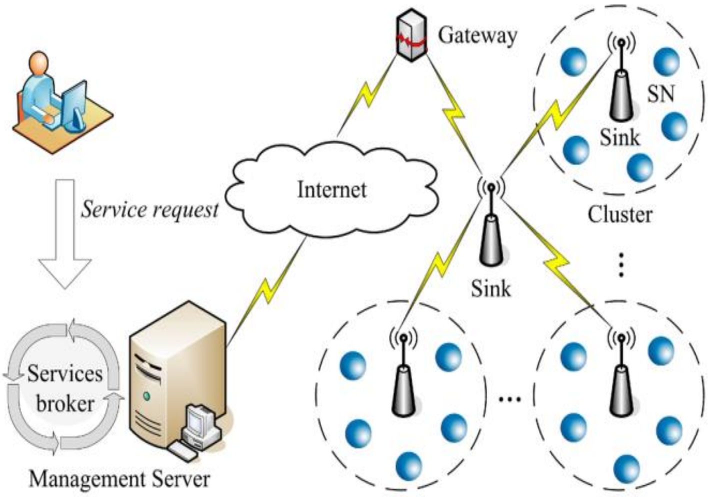

Fig. 2: Clustering WSNs Architecture (Munir, Antoon, & Gordon-Ross, 2015)

While the Low Energy Adaptive Clustering Hierarchy (LEACH) algorithm significantly enhances energy efficiency in Wireless Sensor Networks (WSNs) by organizing nodes into clusters and rotating cluster head (CH) roles, it introduces a notable drawback: the delay in message transmission from the CH to the sink due to data aggregation (Munir, Antoon, & Gordon-Ross, 2015). This necessitates a solution to mitigate data pile-up during the transmission process to ensure timely data delivery. To address energy consumption and enhance reliability in WSN operations, the Residue Number System (RNS) has been adopted. RNS offers a range of advantages including carry-free operations, parallelism, high-speed computation, security, and inherent fault tolerance, making it an excellent candidate for promoting energy-efficient and reliable operations within WSNs (Gbolagade, 2010; Raji & Gbolagade, 2018; Raji et al., 2021). These features are particularly valuable in resource-constrained environments, where it is imperative for nodes to efficiently manage their resources, monitor energy usage closely, and ensure longevity and fault tolerance (Attiah, 2018).

However, the radio component of sensor nodes, responsible for data transmission, is the largest consumer of power within the network. This has led to the proposal of several strategies aimed at reducing energy consumption associated with the radio interface, although these measures often focus on transmission protocols and power-saving modes (Lee, Min, Choi & Lee, 2016; Jindal, 2018). Despite these advancements, there remains a need for further research into energy-efficient and fault-tolerant methodologies suitable for contemporary WSN technologies. As WSNs continue to evolve and find application in increasingly diverse and demanding environments, developing more sophisticated and robust solutions will be crucial in overcoming the challenges of energy conservation and system reliability.

Hamamreh, Haji, and Qutob (2018) introduced the Minimum Residual Hop Capacity (MRHC), an innovative energy-aware algorithm designed to enhance the efficiency of the Low Energy Adaptive Cluster Hierarchical (LEACH) protocol, a cornerstone in wireless sensor network (WSN) operations. By integrating MRHC into the LEACH protocol during the cluster transmission process, this approach aims to reduce energy consumption significantly, extend network lifespan, and increase the volume of data successfully transmitted to the base station.

In parallel, Abdul-Mumin and Gbolagade (2016) contributed to the domain of error detection and correction within WSNs by proposing a scheme based on the Redundant Residue Number System (RRNS) utilizing a novel 5-moduli set $\{2^{2n} + 1, 2^{n+1} + 1, 2^{n+1} - 1, 2^n + 1, 2^n\}$. This approach is notable for its simplicity, efficiency, and the minimization of iterations required for error correction, which in turn reduces both the complexity of the design and the propagation delay, offering a robust solution for maintaining data integrity within WSNs. Further exploring the realm of fault tolerance and energy efficiency, Lee, Min, Choi, and Lee (2016) investigated a new fault-tolerant framework for WSNs, leveraging a multi-agent configuration that includes mobile agents to monitor energy-efficient services within the network. This framework incorporates various agents equipped with fault-tolerant protocols utilizing multi-agent and mobile agent architectures, aiming to optimize network operation despite the challenge of increased end-to-end delay, which stands as the primary drawback of this system.

The challenges of energy utilization and fault tolerance in WSNs are complex and multifaceted, underscoring the inadequacy of single-method solutions. Consequently, a comprehensive, multi-level strategy that harnesses both Residue Number System (RNS) and intelligent multi-agent technologies is proposed. This approach aims to tackle the dual objectives of providing fault tolerance and enhancing energy efficiency across WSN applications, representing a holistic pathway to addressing the operational challenges faced by contemporary wireless sensor networks.

3. METHODOLOGY

The proposed architectural design framework for real-time Wireless Sensor Networks (WSNs) integrates a comprehensive approach to address the challenges of energy efficiency, speed, error control, and fault tolerance. This four-part design, illustrated in Figure 3, leverages the Residue Number System (RNS) for energy-aware routing protocols and intelligent multi-agent technologies to enhance fault tolerance capabilities.

i. **CRT-based Packet Segmentation and Filtering:** The framework initiates with a novel approach to mitigate data accumulation through CRT-based packet segmentation alongside a filter algorithm. This method, aimed at minimizing the data payload transmitted by each node, employs the moduli set $\{2^{n+1}-1, 2^n, 2^n-1\}$ for dividing the information gathered by each node. The architecture progresses through phases of network division into clusters, assignment of

Cluster Heads (CHs), and the efficient split and forward mechanism where nodes segment and forward the received data to the CHs and subsequently to the sink or another CH, thereby reducing communication overhead.

ii. **MRC-based High-Speed Reverse Conversion:** The design incorporates a MRC (Mixed Radix Conversion)-based high-speed reverse converter (HISPREC) tailored for the moduli set $\{2^{n+1}-1, 2^n, 2^n-1\}$, designed to decode packets received from CHs swiftly while maintaining minimal hardware requirements. This component ensures the rapid processing of data packets, enhancing the network's overall speed and efficiency.

iii. **CRT-based Error Control Using RRNS:** At the sink, an error control mechanism based on the Chinese Remainder Theorem (CRT) and Redundant Residue Number System (RRNS) is employed to bolster message reliability. Utilizing both the standard moduli set $\{2^{n+1}-1, 2^n, 2^n-1\}$ and an additional redundant set $\{2^{n+1}+3, 2^{2n} - 3\}$, the system enhances error correction capabilities through maximum likelihood estimation, which involves selecting the most frequently occurring message and discarding outliers, thus ensuring the integrity of transmitted data.

iv. **Multi-Agent-Based Fault Tolerance System:** The final segment of the framework introduces a fault-tolerant system built on the NetLogo platform and C# programming language, employing multi-agent and mobile agent configurations for adaptive fault management in WSNs. This system facilitates the distribution of specific roles to different agents, enabling efficient network management and information sharing among nodes, as depicted in Figure 3.

This holistic framework combines state-of-the-art technologies and methodologies to create WSN applications that are not only energy-efficient and fast but also robust against errors and capable of adapting to failures, ensuring reliable communication even in challenging environments.

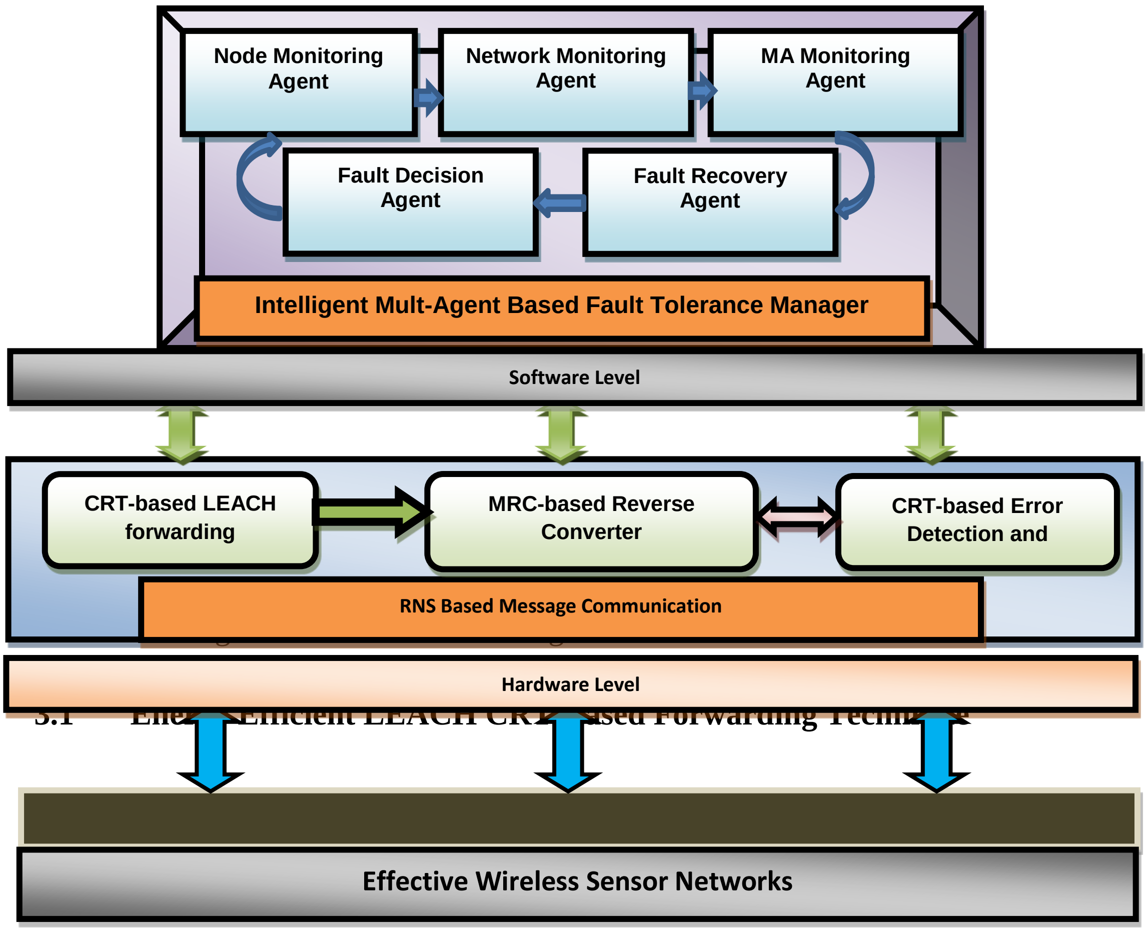

Fig. 3: Architectural Framework

The Low Energy Adaptive Clustering Hierarchy (LEACH) protocol, recognized for its energy efficiency in Wireless Sensor Networks (WSNs), has been further refined by integrating the Chinese Remainder Theorem (CRT) to enhance its original design. This modification aims at reducing data aggregation, a common challenge in network communications, through an innovative packet splitting and forwarding scheme. At the heart of this approach lies the CRT-based forwarding technique, which strategically segments messages from the source node using a predefined moduli set. This segmentation effectively decreases the maximum bit size of packets that a node is responsible for forwarding, thereby conservatively using the network's energy resources and potentially extending the network's lifespan. The segmentation process, facilitated by the CRT, is notable for its simplicity and low computational demand, involving straightforward modular divisions that can be easily handled by the sensor nodes' limited processing capabilities.

In the context of the CRT-enhanced LEACH protocol, the focus shifts from transmitting entire original messages to sending only their residues. This alteration not only contributes to energy savings but also introduces an element of security: to an outside observer or potential intruder, these residue-based packets are indecipherable without knowledge of the specific moduli set used for segmentation. As a result, the modified LEACH protocol not only improves network efficiency and longevity but also inadvertently enhances the confidentiality of transmitted data, as illustrated in Figure 4. This innovative approach underscores the potential of integrating mathematical theorems into network protocols to address both performance and security challenges, promising a more efficient and secure operational framework for WSNs.

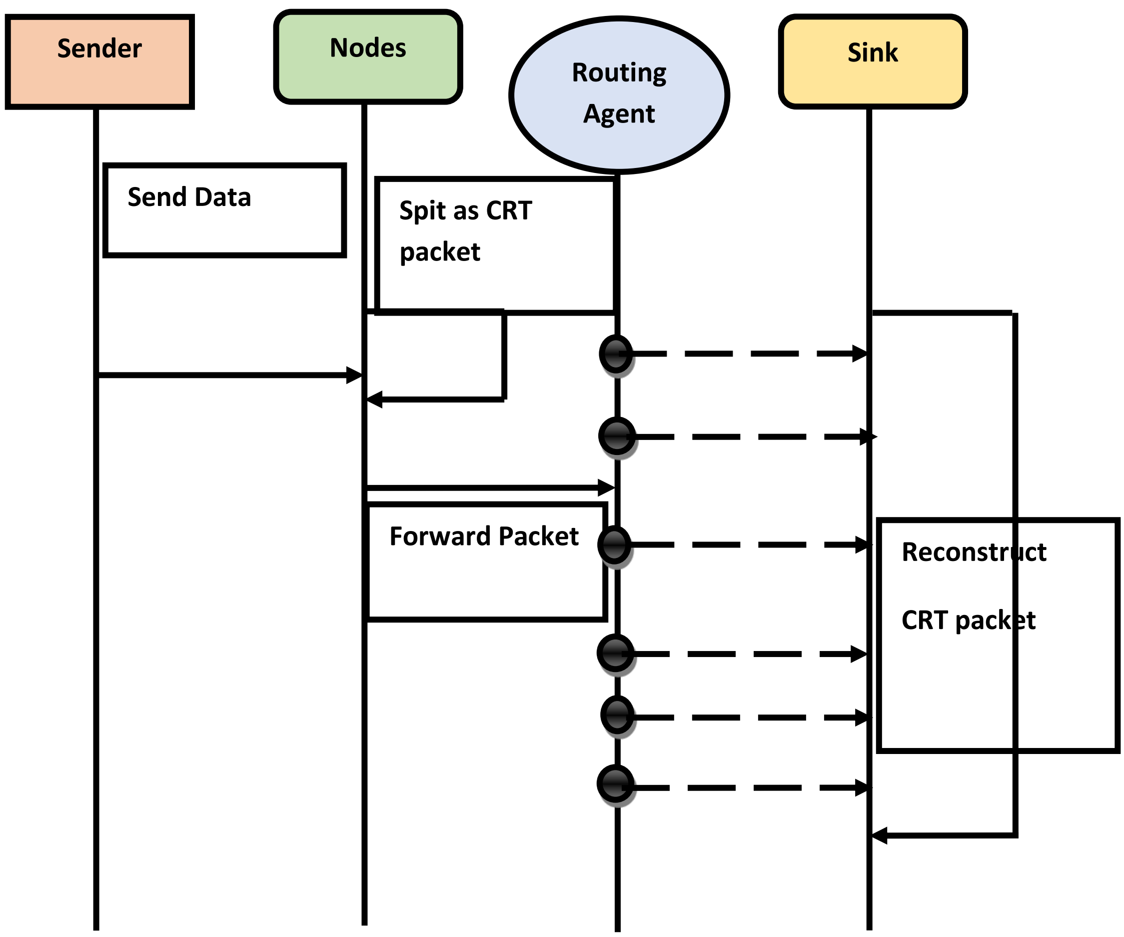

Fig. 4: CRT-Based Forwarding Technique (Singh, Singh & Foujdar, 2014)

Considering the fact that the vitality utilization is proportional to the number of bits conveyed then, assuming n the number of bits in the original message, and nCRTmax (the maximum number of bits of a CRT component), that is;

nCRTmax = max([log2(pi)])…………………………………..

(1)

and considering a theoretical maximum energy reduction factor (MERF) given by:

MERF = $\underline{n - nCRT_{max}}$ ……………………………………… (2)

n

the energy consumption while transmitting will be given as (Hamamreh, Haji & Qutob, 2018):

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d)$$

$$E_{Tx}(k,d) = E_{elec} * k + \in_{amp} k * d^2$$

Where k is the number of packet bits, and d is the distance between sender and receiver.

In the initial phase of establishing a Wireless Sensor Network (WSN) using the adapted Low Energy Adaptive Clustering Hierarchy (LEACH) protocol, the distribution and initialization stage plays a crucial role. During this stage, the sink (base station) orchestrates the network's structural layout by organizing the sensor nodes into clusters. This organization is essential for efficient data communication and energy utilization throughout the network.

Algorithm 1: The Distribution and Initialization Stage

This algorithm outlines the steps taken from the network's structural organization to the initialization of communication protocols within each cluster, ensuring that each node is correctly aligned with its designated CH and that the sink has the necessary data (including the moduli set m_i) to reconstruct original packets from segmented data. Algorithm 1 is given below:

```
Initialize SN=1                                   // To reset an initialized message
While message IM arrives at a nodei
do                                                //IM is initialization message
If CLID = 1                                       //base station is the only node in CLID =
1
Then transmit IM with SN=2 to the next CLID at startup
        Increase SN=SN+1
else
Initialize an array of neighbour with all accessible nodes in the cluster
Use LCF algorithm to select closest nodes for each cluster
Send Join-Request messages
Assign node ID to nodes that accept Join-Request messages
Increase degree of the node, ID = ID + 1
Assign as CH if the residual resources is the highest
                end if
        Get IM with corresponding CLID=j
        Transmit IM to the next CLID
        Increase CLID =CLID +1
All hubs that receives the IM with SN=i assume to belong to CLID=j
        Repeat until all nodes are reached
                end do
```

Split and Forward stage operation activated

The distribution and initialization process are:

1. **Cluster Formation:** The sink evaluates the network and categorizes the nodes into clusters based on specific criteria, such as geographical location and node capability.
2. **Cluster Head (CH) Selection:** Among the nodes within each cluster, a node with relatively higher resources (energy capacity, computational power, etc.) is designated as the Cluster Head. This selection is pivotal for managing the cluster's data communication tasks efficiently.
3. **Cluster Configuration:** The sink determines the optimal number of nodes for each cluster and assigns a unique Identification Number (ID) to them. It also decides on the segmentation of sensed packets, which is crucial for the packet splitting technique to be applied later.
4. **Initialization Messages (IMs) Exchange:** Starting with the sink (considered as Cluster ID, CLID = 1), Initialization Messages are broadcasted across the network. These messages contain information about the cluster configuration and instructions for the packet splitting mechanism.
5. **Dynamic Cluster Membership:** Upon receiving an IM, a node identifies its cluster membership (CLID) based on the sequence number (SN) in the IM. It then forwards the IM to its neighbors, incrementing the SN, thus dynamically forming the cluster structure.
6. **Cluster Member Selection:** Using the Lowest Common Factor (LCF) or another suitable algorithm, the final selection of cluster members is made, ensuring that each node is aware of its CH and fellow cluster members.

Algorithm 2: Splitting and Forwarding Stage

This algorithm provides a detailed procedure for segmenting sensed data and efficiently transmitting it through the network, leveraging the unique advantages of the CRT-based packet splitting technique to minimize energy consumption and enhance the network's lifespan and scalability. This is given below:

While Nodei sensed message
do
If cluster member = 1
Then send packet without splitting
else
Use CRT with the moduli set to split the packet into number of members in the cluster
Send Xi = x(mod mi) to CH
If cluster node = CH
Gather the packets in order to have all the residues
Use LCF to forward xi to another CH until it gets to the Sink
elseif node = sink
Then reconstruct using
End if
End do

Once the clusters are formed and each node is aware of its CH, the packet splitting and forwarding process begins. This involves:

1. **Data Segmentation:** Each node splits its sensed data according to the predefined moduli set mi, as directed by the sink during the initialization phase.
2. **Efficient Communication:** The CH acts as the communication hub within the cluster, facilitating data exchange between its members and ensuring the data is correctly forwarded to either the sink or other CHs in the network.

The coordination between these algorithms ensures the network operates efficiently, balancing energy consumption with the need for reliable and secure data communication. In this enhanced approach to data communication within Wireless Sensor Networks (WSNs) using the LEACH protocol, a novel methodology is introduced that significantly reduces the need for traditional data aggregation, thereby optimizing energy consumption and improving network efficiency. This process is particularly noteworthy for its implementation of residue-based data transmission and the pivotal role of the Cluster Heads (CHs) in managing this process. The step-by-step breakdown:

i. **Residue Transmission:** Each sensor node, upon sensing data, calculates a residue based on its unique identification (ID) within its cluster. This calculation is aligned with a predefined moduli set, which is crucial for the subsequent reconstruction of the original data.

ii. **Direct CH Communication:** Instead of aggregating data for preliminary processing, sensor nodes directly send these residues to their respective CH. This approach minimizes computational overhead on the nodes and reduces the data volume transmitted, leading to significant energy savings.

iii. **Residue Collection by CH:** Upon receipt of all the residues from its cluster members, the CH compiles these pieces. This collection does not involve traditional aggregation or fusion of data, but rather, the CH acts as a relay point for these residues.

iv. **Forwarding to CH or Sink:** The CH then forwards the collected residues either to another CH or directly to the sink. This step is critical in the hierarchical data transmission process and ensures that data moves efficiently towards the sink for final processing.

v. **Original Message Reconstruction:** At the sink, the final step involves reconstructing the original message from the received residues using the moduli set. This process leverages the Chinese Remainder Theorem (CRT) or similar mathematical frameworks, enabling the sink to accurately derive the original sensed data from the residue information.

3.1 Development of MRC-Based High Speed Reverse Converter (HISPREC)

The development of the High-Speed Reverse Converter (HISPREC) represents a significant advancement in the field of Wireless Sensor Networks (WSNs), particularly in the context of efficient data processing and power management. By adopting the Residue Number System (RNS) for data encoding, HISPREC capitalizes on the unique benefits offered by RNS, notably its ability to facilitate parallel processing and reduce computational complexity. This is particularly advantageous in a WSN environment where power and processing capabilities are limited. The selection of the moduli set {2n+1-1, 2n, 2n-1} for HISPREC is strategic, aligning with the system's goals of high-speed conversion and power efficiency. This choice is informed by the characteristics of the moduli set, which influences the complexity and performance of the reverse conversion process. By basing HISPREC on Mixed Radix Conversion (MRC), the system effectively harnesses a method known for its efficiency in converting between different numbering systems.

In the operational context of a WSN, the role of Cluster Heads (CHs) is pivotal. They act as aggregation points that collect data from sensor nodes, perform initial processing, and then transmit this data towards a central sink. Traditionally, this data is transmitted in its original form, consuming significant amounts of energy and bandwidth. However, with HISPREC, CHs transmit the residue-encoded data instead, significantly reducing the energy required for transmission and the bandwidth needed. Upon receipt of this residue-encoded data, the sink employs HISPREC to decode the residues, reconstructing the original data. This process benefits from the high-speed conversion capabilities of HISPREC, enabling the rapid processing of incoming data streams. Moreover, the energy efficiency of HISPREC plays a crucial role in extending the operational lifespan of the sink and, by extension, the entire WSN. In essence, HISPREC exemplifies a sophisticated approach to data conversion in WSNs, addressing the critical challenges of speed and power consumption. Through the intelligent use of RNS and MRC, along with a carefully selected moduli set, HISPREC enhances the overall efficiency and performance of WSNs, demonstrating the potential of advanced mathematical tools and systems design in tackling real-world technological challenges.

3.2 Designing of CRT-Based Error Control Scheme

This section presents methodology for an efficient and low vitality utilization error control scheme that makes use of RRNS to boost the integrity of received message in real-time WSNs. In order to realize the proposed scheme, the moduli set $\{2^{n+1}-1, 2^n, 2^n-1\}$ is utilized to design CRT-based error control scheme with additional redundant moduli set $\{2^{n+1}+3, 2^{2n}-3\}$. As shown in Figure 3.6, a node sends a residue (based on its position in the cluster) of the sensed message to the CH, the CH in turn forwards gathered residues in its cluster to the sink node which in turn converts the received residues to binary equivalent. It also checks for errors, corrects the errors, then recovers the sink from error to produce error free message. Similarly, for error control scheme, it is required that the moduli set $\{2^{n+1}-1, 2^n, 2^n-1\}$ be relatively prime numbers. The error can be detected if $a_j \neq 0$ with j [k+1, n]. Assuming a single error corrupt the ith residue digit in the residue of the received integer

X, this is represented as an addition of the number ei to the residue while 0 <ei<mi, that is: where X’ is the altered number. Similarly, X’ can be defined as the sum of the X and an integer E formed by the residue ei.

3.3 Development of Intelligent Multi-Agent System Based Fault Tolerant

The development of an Intelligent Multi-Agent System Based Fault Tolerant mechanism represents a significant advancement in the resilience and efficiency of Wireless Sensor Networks (WSNs). By leveraging the flexibility and autonomy of mobile agents, this approach introduces a dynamic method of managing and recovering from faults within the network. In the proposed system, agents are imbued with the capability to migrate across the network autonomously. This migration is not merely a relocation but a strategic transfer of both the agent's code and its current state to a designated node. Such a capability ensures that the agents can continue their assigned tasks with minimal disruption, thereby maintaining the network's integrity even in the face of node failures or other anomalies. The organizational structure of these agents within the WSN is both innovative and practical. By adopting a clustering-distributed method for fault detection, the network is segmented into various clusters, each overseen by a dedicated agent. These agents, equipped with the necessary code and parameters for their mission, are responsible for the initial detection and management of faults within their respective clusters. This segmentation facilitates a more manageable and focused monitoring system, allowing for quicker identification and response to potential issues.

For fault recovery, the system employs a hierarchical model, offering a layered approach to addressing and rectifying faults. This model ensures that while individual agents handle immediate concerns within clusters, a broader, more centralized strategy is available for complex or widespread issues. Such a dual approach combines the efficiency of distributed processing with the comprehensive oversight of centralized management, ensuring a robust and adaptable fault tolerance mechanism. Figure 5, referenced in the study, presumably illustrates this dual-structured approach, showcasing how agents are distributed across clusters for fault detection and how the hierarchical model integrates these efforts into a cohesive fault recovery strategy. This visualization likely aids in understanding the operational dynamics of the system and how individual components interact to ensure network resilience.

In summary, the development of an Intelligent Multi-Agent System Based Fault Tolerant mechanism for WSNs represents a significant leap forward in network management and resilience. By intelligently combining distributed and hierarchical methodologies with the dynamic capabilities of mobile agents, this approach ensures that WSNs can maintain operational integrity and quickly recover from faults, making them more reliable and efficient in fulfilling their roles in various applications.

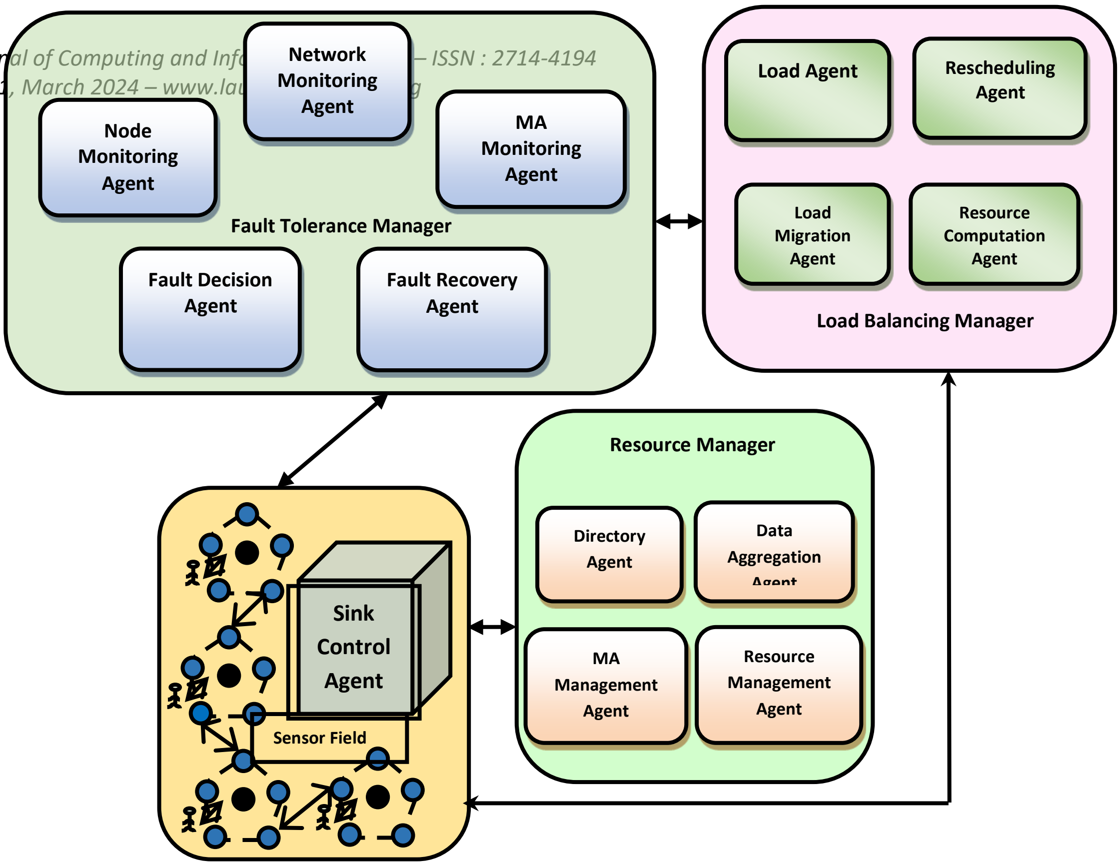

Fig. 5: Architecture of Clustering-Distributed WSNs with Agents

Then for the hierarchical fault recovery, the CH manages all nodes in its sub-network by getting reports from different utility agents and send to the sink if need be. Mobile software agent was implemented in C# and Netlogo by writing different generic software agent codes with individual utility tasks to run autonomously and continuously in sensor environment.

4. ANALYSIS OF EFFECTIVE WIRELESS SENSOR NETWORKS

Addressing the challenge of developing consistent and scalable network architectures is pivotal, particularly in the context of Wireless Sensor Networks (WSNs). The techniques used include a CRT-based forwarding strategy, a high-speed reverse converter, an error control scheme, and an agent-based fault tolerance approach. Collectively, these innovations represent a significant stride towards effective WSNs. To rigorously assess the performance of these proposed nodes, extensive simulations were conducted using the Probabilistic Wireless Network Simulator (Prowler) within a MATLAB environment. MATLAB's interactive environment, coupled with its array of precise mathematical functions, and Prowler's ease of use for application prototyping and wireless distributed systems simulation, provide an ideal testing ground. The simulations varied the number of sensor nodes deployed randomly, starting with a minimum of 10 nodes within a 150 x 150 square meter field. Each sensor node was assigned a unique identifier, and it was assumed that the nodes would remain stationary post-deployment. Through this meticulous simulation-based evaluation, the study aims to not only demonstrate the practicality and effectiveness of the proposed techniques but also to shed light on their potential to significantly improve the scalability, reliability, and overall performance of WSNs in handling real-time data traffic.

Energy efficiency is characterized as the aggregate unused vitality level of hubs in the system. Node vitality consumption is defined as the communication (transmitting and receiving) energy the network consumes excluding the idle energy. Assume a continuous time between t_1 and t_2 for the energy consumption measurement. Residual energy in time t is defined by omitting consumed energy in Δt, from the initial battery power in t-Δt. Thus, the energy consumption will be determined in Δt as:

$$\begin{cases} E_{residual},i(t_2)=E_{residual},i(t_1)-E_{consumed},i(\Delta t) \\ E_{consumed},i(\Delta t)=\frac{\partial E_{residual},i(t)}{\partial t}\Delta t \\ \Delta t=t_2-t_1 \end{cases}$$

Energy consumption of the processor unit in an active state depends on the number of processed bits (b_{proc}), its operating voltage and frequency, is:

$$e_{1,tive}\ (\Delta t) = F_1\ (f, b_{proc}.)$$

Moreover, power consumption of a hub unit in an active state relies on the sensor radius (r_{sense}), the data generation rate (g_{sense}), and the number of generated bits (b_{sense}) as:

$$e_{2,tive}\ \Delta t = F_2\ (r_{sense}, g_{sense}, b_{sense})$$

In addition, vitality consumption of a memory unit in an active state depends on the number of stored bits (b_{store}), the number of memory read (e_{rd}) and write (e_{wt}), and the duration of storage (t_{store}) is:

$$e3_{,tive}\ \Delta t = (F_3 b_{store}, e(_{rd})\ , e(_{wt})\ , t_{store})$$

Furthermore, energy consumption of nodes from a sink constituent viewpoint can be formulated as:

$$E_{snk,}(\Delta t) = K(e_i(snk)),$$

where $e_i(snk)$ shows energy consumed by each node to communicate with the sink and perform the sink's requests.

Lastly, power utilization of the transceiver unit for message transmission in an active state depends on the number of received (b_{Rx}) and transmitted bits (b_{Tx}), and the amount of needed energy for coding (e_{code}) and decoding packets (e_{decode}) as:

$$e4_{,tive}\ \Delta t = F_4(b_{Rx}, b_{Tx}, e(code)\ , e(decode))$$

Table 1 displays the energy consumption by different numbers of nodes using three different schemes. Figure 6 displays the energy consumption by each node using three different approaches. In proposed CRT-based LEACH forwarding technique energy efficiency reach the level of 0.17 while MRHC-LEACH and shortest path techniques attain 0.224 and 0.275 respectively.

Table 1: Energy Consumption by Each Node

No of Nodes/ Energy Spent(joule)	**5**	**20**	**30**	**50**	**60**	**70**	**80**	**90**	**100**
CRT-based LEACH	0.07	0.15	0.17	0.135	0.15	0.15	0.15	0.15	0.15
MRHC-LEACH	0.09	0.22	0.23	0.20	0.223	0.224	0.224	0.224	0.224
Shortest Path (Anton, 2015)	0.12	0.25	0.26	0.228	0.275	0.275	0.275	0.275	0.275

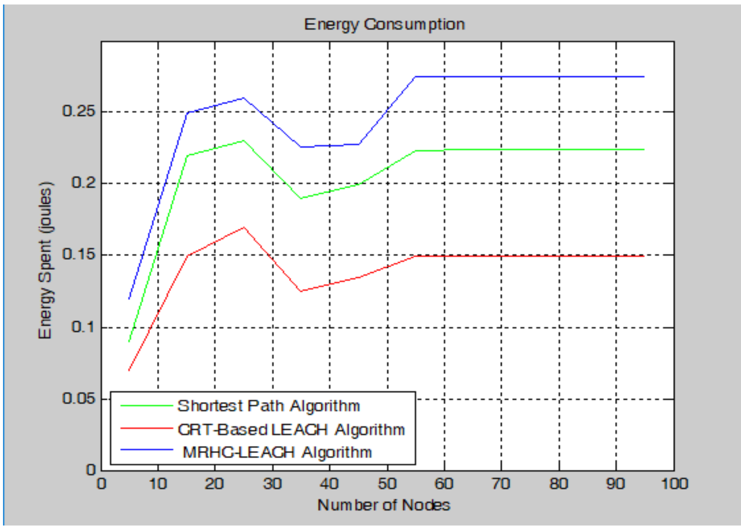

Fig. 6: Energy Consumption by Each Node

Table 2 shows the sensor node lifetime by different numbers of nodes using three different techniques. Figure 7 demonstrates the network lifetime for various number of sensor nodes (i.e., n = 10…100) for the proposed scheme and two other schemes. Network lifetime is usually 'the lifespan of the first node in all sensor nodes that depletes its energy.

Table 2: Sensor Network Lifetime

No of Nodes/Time (Seconds)	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
CRT-based LEACH	198	231	261	279	291	331	380	420	445	460
MRHC-LEACH	101	111	120	133	146	182	201	241	261	282
Shortest Path (Anton, 2015)	85	91	115	121	132	141	152	161	173	190

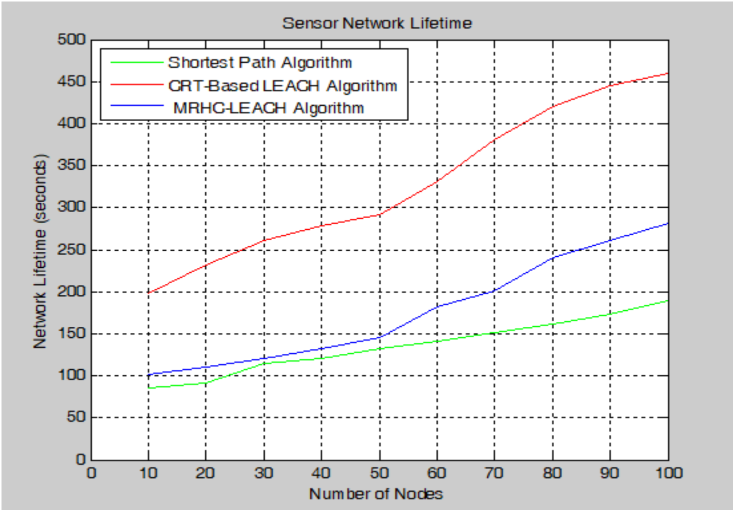

Fig. 7: Network Lifetime

As depicted in Table 3 and Figure 7, our proposed CRT-based LEACH scheme consistently maintains a longer network lifetime across all tested node quantities, reinforcing the robustness and energy efficiency of our design. Particularly, in denser networks of 100 nodes, our technique outperforms the Shortest Path method by 142.11% and MRHC-LEACH by 63.12%, highlighting its superior scalability.

Table 3: Area and Delay Comparison of the Reverse Converter

Reverse Converter	Moduli Set	Area (A_{FA})	Delay (t_{FA})
Bankas and Gbolagade (2014)- **BG [14]**	$\{2^n, 2^n + 1, 2^n - 1, 2^{2n+1} - 1\}$	12n+2	9n+6
Barati, Movaghar and Sabaei (2014)- **BMS [14]**	$\{2^{2n+1}, 2^{2n+1}-1, 2^n-1\}$	7n+3	9n+8
Raju, Kumar and Divya (2014)- **RKD [14]**	$\{2^n+1, 2^n-1, 2^{2n}, 2^{2n+1}-1\}$	10n+2	14n+3
Habibi and Salehnamadi (2016)- **HS [16]**	$\{2^n-1, 2^n+1, 2^{2n}-1\}$	7n + 1	10n + 6
Proposed (HISPREC)	$\{2^{n+1}-1, 2^n, 2^n-1\}$	6n +2	9n +2

The proposed HISPREC stands out as the most efficient design, achieving the optimal balance between area and delay, indicating its effectiveness for use in wireless sensor networks where both resource utilization and processing speed are critical. From the result in table 3, the proposed moduli set have dynamic range of 3n + 1 which is sufficient enough for a fairly arithmetic unit speed in WSNs. Similarly, the proposed moduli set also has an area of (6n +2)A¬FA which provide low hardware requirements, cost and power usage; also, a delay of (9n +2)tA¬FA that provides relatively low conversion delay and high performance for the WSNs in terms of energy usage.

Table 3: Simulation of Results on Hardware Realization

Schemes	Energy Usage and Network Lifetime	Hardware Requirements	End-to-End Delay
BG [14]	13	34	33
BMS [14]	11	17	20

RKD [14]	11	26	24
HS [16]	12	17	26
Proposed (HISPREC)	7	14	24

The proposed HISPREC scheme demonstrates superior performance in energy usage and hardware requirements, indicating it is the most energy-efficient and has the lowest hardware complexity among the schemes evaluated. This makes it particularly suitable for applications where energy and resource efficiency are critical. While the end-to-end delay of HISPREC is not the lowest, it offers a balanced trade-off by maintaining competitive speeds without sacrificing energy efficiency or hardware simplicity. This balance is crucial for wireless sensor networks where both energy consumption and timely data transmission are important. Overall, HISPREC's performance across these three metrics underscores its potential for effective deployment in real-world wireless sensor networks, offering an appealing solution that balances efficiency, simplicity, and speed.

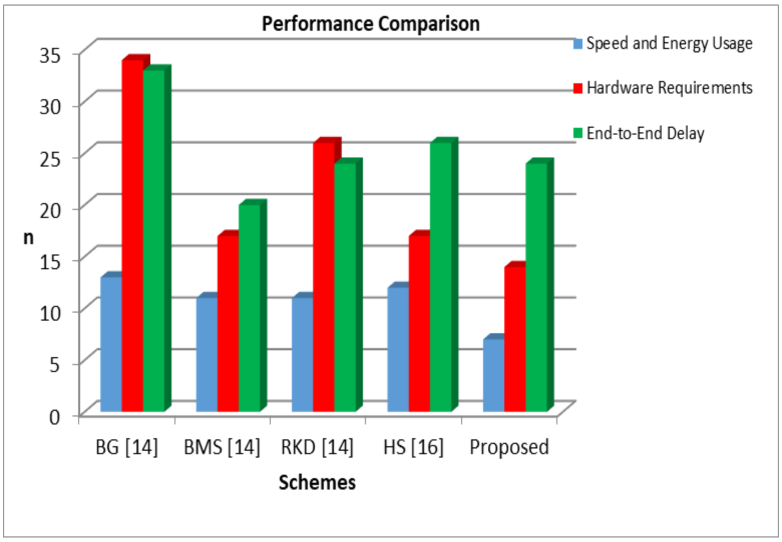

Fig. 8: Performance Comparison

This detailed approach presents an integrated fault recovery strategy for wireless sensor networks (WSNs) that effectively combines centralized and distributed mechanisms for enhanced reliability and robustness. By assigning the Cluster Head (CH) the role of central coordinator within its sub-network, the system ensures that potential issues are addressed promptly and efficiently, minimizing the impact on the network's overall performance. The hierarchical method enables targeted fault recovery actions, such as isolating faulty nodes and redistributing correct software codes, thereby maintaining the network's integrity and operational efficiency. The inclusion of the sink as an overarching monitoring entity adds an additional layer of fault tolerance, ensuring the entire network remains resilient against failures. Agent based approach has about 56.1% energy consumption reduction than non-agent based approach as shown in figure 4.29.

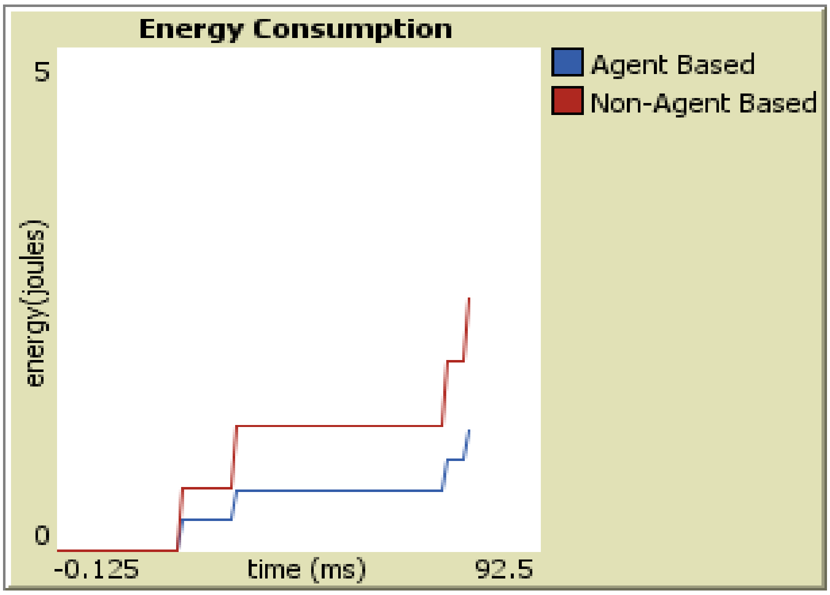

Fig. 9: Simulation Model for Energy Consumption

Figures 10 and 11 likely provide a visual representation of this fault recovery process, highlighting the key roles and interactions that underpin this approach. This strategy underscores the importance of adaptability and comprehensive oversight in maintaining the functionality of complex WSNs in the face of various fault scenarios.

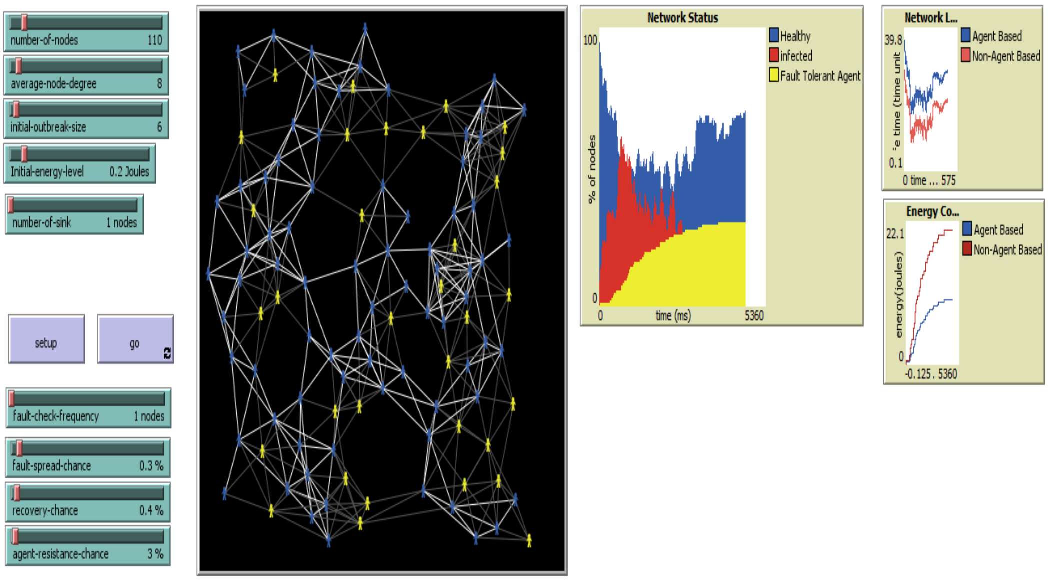

Fig. 10: Netlogo Simulation Model for WSNs Environment with Suspected Nodes

Figure 10 indicated that agent based technique has about 40.5% better network tolerant when compared with non-agent based approach. Additionally, Figure 11 shows that agent based approach has 49.3% better advantage of code redistribution than non-agent based approach.

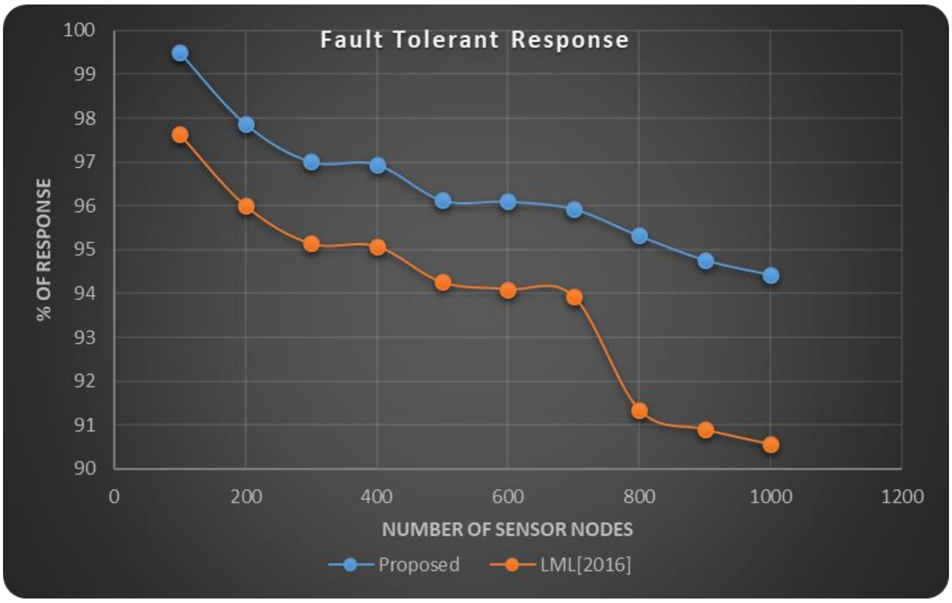

Fig. 11: Performance Evaluation Proposed Scheme and LML [2016]

5. CONCLUSIONS

The study introduced an enhanced energy-efficient wireless sensor network (WSN) strategy that incorporates a CRT forwarding technique with the LEACH protocol, significantly improving power efficiency, reliability, and message delivery times compared to the original LEACH protocol and shortest path routing methods. A key component of the proposed system is the High Speed REverse Converter (HISPREC), tailored for a specific moduli set, which demonstrates superior performance in hardware efficiency, energy consumption, and data conversion speed against other reverse converters under similar conditions. Furthermore, an advanced error control scheme was developed for real-time WSNs, utilizing a specific moduli set along with additional redundant moduli for optimal error correction. This system stands out for its error detection and correction capabilities in real-time WSN environments. The study also introduced a novel fault-tolerant WSN framework employing an intelligent multi-agent system for efficient sensor data management and storage. Utilizing the Netlogo agent framework and C# for development, this approach integrates various types of agents, including node monitoring, network monitoring, mobile agent monitoring, fault decision, and fault recovery agents, to enhance network efficiency, speed, reliability, and fault tolerance. The research highlights the potential of intelligent mobile agents in maintaining sensor networks and suggests that agent-based WSNs could offer significant advantages over traditional non-agent-based systems in terms of energy consumption, operational speed, reliability, and fault tolerance.

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