Innovative Energy-Efficient Hierarchical Clustering Protocol for Wireless Body Area Networks Using the Firefly Algorithm

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ABSTRACT:
Wireless Body Area Networks (WBANs) are essential in healthcare-related applications, relying on sensor nodes to monitor physiological parameters. A major limitation of WBANs is the limited battery life of these nodes, making energy efficiency a critical factor, particularly due to the impracticality of frequent battery replacements. To address this issue, the present study introduces a novel hierarchical clustering strategy based on the Firefly Algorithm (FA) to optimize energy consumption within WBANs. The performance of the proposed method is assessed across three distinct scenarios. In the first scenario, sensor nodes are positioned randomly following the IEEE 802.15.6 communication standard, utilizing a linear topology and full 360-degree coverage. The second scenario continues with random node placement but integrates the FA for cluster formation, a technique termed Firefly-Based Clustering (FBC). The third scenario adopts the NODIC protocol for clustering, where designated cluster heads (CHs) relay collected data to a central sink node. Simulation experiments conducted in OPNET 11.5 demonstrate that the proposed FBC approach significantly reduces energy usage and extends network longevity compared to both the traditional NODIC protocol and the IEEE 802.15.6 standard.

KEYWORDS: Clustering, Wireless Body Area Network, Firefly Algorithm, NODIC Protocol.

1. INTRODUCTION

In industrialized countries, in-home patient health tracking has gained prominence, driven by an aging population and the escalating costs of healthcare services. This shift has been facilitated by the advancement of biomedical sensors, which support continuous remote monitoring of patients' vital signs. Wireless Sensor Networks (WSNs), a specific form of wireless ad-hoc networks, are designed using a network of distributed sensor nodes. These nodes are tactically placed to observe a range of physical or environmental parameters, including but not limited to motion, temperature, vibration, pressure, acoustic signals, and the status of the monitored environment [1]. In such networks, sensor nodes are densely deployed over a target area to gather sensory data. This data is relayed from individual nodes to a central base station commonly referred to as the sink, often through multiple relay nodes. The sink is responsible for storing the incoming data for further evaluation. However, both the transmission of data from sensor nodes and its processing at the sink consume substantial amounts of energy. As a result, conserving energy within sensor nodes is essential to extend the overall network operational period. One practical approach to reduce energy drain during data transmission is the design of energy-aware routing schemes. Among the existing solutions, clustering-based techniques are widely recognized for their efficiency. In such methods, sensor nodes are organized into clusters, each managed by a designated CH, which coordinates intra-cluster communication and forwards aggregated data to the sink [2]. In WSNs, appointing CHs for

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managing data transmission significantly contributes to lowering energy usage. When these CHs are positioned near the central sink or base station, they can transfer data directly, thus conserving energy. Conversely, if the CHs are situated at greater distances from the sink, data must be relayed through multiple CHs in a multi-hop manner, increasing energy expenditure. Furthermore, when a sensor node remains in the role of a CH for prolonged durations, its energy depletes rapidly, which can negatively impact the overall network longevity. With the evolution of wireless communication technologies, real-time data acquisition and online transmission have become viable. Modern smart home systems can now send patient health data to a centralized digital platform, allowing access for patients, healthcare providers, and caregivers alike. These systems are not only useful for patients with existing medical conditions but also for health-conscious individuals seeking to track their wellness metrics. Wearable biomedical sensors are at the core of such systems, offering continuous monitoring of physiological parameters including cardiac rhythms, muscular movements, and general mobility. These sensors are key enablers of mobile healthcare systems, transmitting health data securely to authorized users and allowing remote diagnosis and monitoring. The integration of advanced mobile technologies has further supported these efforts by enabling efficient data processing, storage, and analytical capabilities [3]. Recent technological breakthroughs in physiological sensors, low-power electronics, and wireless communication protocols have led to the emergence of Body Area Networks (BANs). BANs are specialized forms of WSNs designed for applications across diverse sectors such as transportation, agriculture, structural monitoring, and especially healthcare. In medical contexts, BANs facilitate seamless updates to patient records and support cost-effective, continuous connectivity. These networks employ state-of-the-art wearable sensors that are both reliable and comfortable, making them suitable for use in applications like digital rehabilitation systems and early disease detection. Moreover, implanted biosensors within the human body offer real-time health monitoring by capturing various physiological indicators and transmitting the data wirelessly to external devices for further processing. Despite their benefits, BANs also face significant limitations—chief among them being restricted battery life. Since sensor nodes rely on finite energy sources and are often difficult to recharge—particularly when implanted—enhancing energy efficiency is a key research focus. Clustering techniques serve as an effective solution in this context by reducing energy demand, especially during inter-cluster communication, where information is exchanged between nodes and their respective CHs [4]. Reducing the distance between sensor nodes and their corresponding CHs is a key strategy for minimizing energy usage in Body Area Networks (BANs) [5]. Cluster-based communication techniques aim to extend the operational lifespan of the network by lowering communication overhead, establishing optimal routing paths, and enhancing both intra-cluster and inter-cluster data exchange efficiency [6]. As a result, the development of energy-aware routing strategies becomes vital for sustaining network functionality over time. This study addresses hierarchical structures within BANs and introduces a novel clustering mechanism powered by intelligent optimization, specifically the Firefly Algorithm, to enhance energy efficiency among sensor nodes. To assess the performance of the proposed approach, simulations are carried out using OPNET version 11.5 [7]. The effectiveness of the method is benchmarked against two established models: the NODIC protocol [8] and the IEEE 802.15.6 standard, which is widely implemented in BAN environments. Key evaluation criteria include end-to-end transmission delay, energy consumption levels, signal-to-noise ratio (SNR), and overall data throughput.

1. RELATED WORKS

Due to the unique requirements of WBANs, sensor nodes used in such systems must be compact, affordable, and energy-efficient. However, this leads to inherent limitations, particularly regarding restricted power capacity. Numerous studies have sought to address these limitations by proposing strategies that focus on energy preservation. Among these, clustering has proven to be a highly efficient approach for organizing the network and managing communication among nodes. While dynamic clustering and the periodic reelection of CHs generally consume limited energy, the initial setup and coordination phases—such as forming clusters and selecting heads—can result in notable energy expenditure due to the volume of control messages exchanged. A major ongoing challenge in WBSNs is ensuring reliable and timely data delivery, especially for applications like elderly healthcare monitoring. Performance issues such as inconsistent data transmission, significant latency, and high power consumption further complicate this objective. To tackle these challenges, the study presented in [9] introduces an algorithm called Enhanced Reliability, Energy-Efficient, and Latency-aware (EREEAL), designed specifically to improve the accuracy and efficiency of data communication in WBSNs. EREEAL reduces packet loss, decreases latency, and improves overall communication reliability by leveraging Time-Division Multiple Access (TDMA), allowing sensors to transmit data in designated time intervals. Additionally, it limits the transmission of repetitive or non-essential data, leading to significant energy savings. Simulation findings confirm that the EREEAL algorithm enhances communication stability, lowers delay, and reduces power consumption. This contributes to more efficient remote patient monitoring by reducing interference among sensors and limiting data loss. By optimizing network performance and ensuring timely, accurate health data transmission, the method allows healthcare providers to perform continuous, remote diagnostics with greater reliability. In [10], a protocol known as

Energy-Aware Routing (EAR) is introduced, specifically aimed at reducing power consumption in BANs by analyzing the quality of wireless links. The EAR approach integrates two essential parameters—residual energy and link stability—into its decision-making framework for route selection. Each node evaluates neighboring links and remaining energy levels to determine the optimal forwarding path using a weighted formula. This formula considers factors such as initial battery capacity, signal reliability, and the node's current energy status. The objective of this strategy is to evenly distribute the communication load among nodes, enhance routing efficiency, and extend the network's operational life. Simulation-based validation was conducted to assess the protocol's performance across several criteria, including energy usage, packet delivery success, network delay, and throughput. The outcomes demonstrated that the EAR protocol significantly reduces power drain while maintaining effective and dependable data transmission within WBAN environments.

Furthermore, the research presented in [11] introduces a robust multi-path routing protocol designed to deliver stable and efficient communication in WBANs. This protocol emphasizes both service quality prediction and intelligent bandwidth utilization. It employs Time-Division Multiple Access (TDMA) for structured communication, enabling optimal bandwidth management. The protocol continuously evaluates service quality by sustaining reliable routes between source and destination nodes. When data transmission is initiated, it identifies unused time intervals (idle slots) and calculates available bandwidth based on the current connectivity between nodes. Additionally, it enhances route stability by monitoring mobility trends, collecting statistical data on adjacent nodes, and estimating link expiration durations. These predictive capabilities help preserve route integrity and support timely route repairs, minimizing interruptions in data flow. While the protocol excels in load balancing, data scheduling, and link resilience, it does require additional bandwidth for its routing operations. This can lead to elevated power demands on individual nodes, potentially shortening their battery lifespan despite improved communication performance. In [12], the authors propose an energy-optimized routing protocol tailored for WBANs, with the goal of enhancing power efficiency during data transmission. This protocol designates two nodes responsible for handling sensitive data and introduces a cost function based on two primary parameters: the shortest communication distance and the highest available energy. Since longer transmission distances inherently require more energy, minimizing distance is a key factor. Additionally, energy thresholds are established, and nodes that are depleted or close to depletion are given lower priority. The protocol adopts a two-tiered approach—routine data is transmitted via multi-hop routing to conserve energy, while critical information is sent directly through a single-hop path to ensure speed and reliability. The sender node's role involves gathering data and forwarding it to the sink node, dynamically choosing relay nodes based on their proximity to the sink and their residual energy levels. Signal strength or link quality is also a critical criterion when selecting the forwarding node. It's worth noting that a sensor with a high energy reserve might not always have a stable communication link, highlighting the need to consider both energy and signal integrity when establishing connections.

Separately, radiation therapy remains a key method in the treatment of cancer, targeting tumor cells with high-energy rays to either eliminate or restrict their proliferation. Precision in targeting is crucial, as even slight patient movements or respiratory activity can alter the tumor's position during therapy sessions. To counteract this, real-time tracking of tumor movement is essential to ensure accurate radiation delivery while sparing surrounding healthy tissue from exposure.

In [13], the researchers present a novel tumor-tracking method based on spatial sparsity principles. Their approach employs a radio frequency (RF) emitter embedded within the body to generate signals, which are then captured by a strategically placed array of sensors located beneath the patient. These signals are processed to accurately determine the tumor's location. Unlike conventional techniques that typically depend on magnetic transmitters and numerous sensors, this method achieves high precision with fewer sensing elements. Two testing scenarios were explored: one with clearly defined tissue structure and another with uncertain or poorly defined tissue boundaries. In both cases, the approach demonstrated strong accuracy, making it a promising alternative for real-time tumor localization, particularly in clinical settings where tissue delineation may be challenging. Energy efficiency is a pivotal concern in the design and operation of WSNs, as reducing power usage is crucial for extending the operational lifespan of individual sensor nodes. In response to this need, researchers in [14] propose a novel routing framework for WBASNs that integrates a clustering algorithm to minimize energy consumption. This method emphasizes a centralized clustering strategy to create a tree-like routing structure among sensor nodes, thereby shortening communication distances. By enforcing a uniform cluster layout, the approach ensures that nodes are evenly distributed. The clustering process accounts for both the spatial distance between nodes and their remaining energy levels, enabling the strategic selection of source nodes. Within each cluster, a multi-phase adaptive mechanism is employed to optimize intra-cluster communication by limiting data transmission ranges. This strategy balances energy use across the network and reduces data forwarding costs. Simulation outcomes confirm that this method leads to notable reductions in energy expenditure, thereby extending the active life of sensor nodes and improving overall network efficiency.

In [15], the authors explore an innovative technique that utilizes backup, or "reserve," nodes to limit the frequency of message exchanges in clustering-based protocols, thereby conserving energy. This reserve mechanism is specifically designed to reduce the overhead incurred during cluster formation and the election of CHs. The proposed algorithm introduces a reserve phase during the initial setup of the network. By activating this phase early in the network's lifecycle, the approach significantly lowers the number of control messages needed during dynamic clustering operations. The algorithm's performance is benchmarked against the LEACH protocol, and results demonstrate that the inclusion of reserve nodes can markedly enhance energy conservation and extend network longevity. This strategy proves effective in managing communication load while maintaining network functionality with reduced power consumption. In paper [16], the authors introduce a novel exploratory routing algorithm, the QoS Multi-objective Hybrid Routing Algorithm (Q-MOHRA), specifically designed for heterogeneous sensor networks. Q-MOHRA evaluates multiple factors, including energy consumption, link quality, and route delay, when determining the optimal route for data transmission. The primary goal of this algorithm is to ensure service quality across the network by simultaneously addressing various objectives. By integrating considerations of energy efficiency, link quality, and route delay, Q-MOHRA enables well-informed decisions about the best path for data transmission, ultimately improving overall network performance while balancing energy consumption and ensuring reliable data transfer.

3. THE SUGGESTED METHOD

The limited energy resources in sensor nodes make it essential to optimize energy consumption in order to extend the lifespan of WSNs. The development of routing protocols based on intelligent methods can significantly contribute to enhancing network longevity. This paper proposes the use of the FA to design an efficient clustering algorithm for WSNs, with the primary goal of improving energy efficiency. In a different context, fireflies display a fascinating natural phenomenon through their luminous flashes, which are visible in tropical and temperate regions during the summer months. There are approximately 2,000 species of fireflies, each producing unique and short-lived flashes. The mechanism behind flash production, known as bioluminescence, remains an area of ongoing research and debate. Fireflies use these flashes for two main purposes: attracting mates and capturing prey. The patterns of the flashes, their rhythmic nature, flash rates, and the distances between signals are critical for firefly communication within species. Females respond to the flashes emitted by males, while some species, such as Photuris, mimic the flashes of other species to deceive and prey upon them. The intensity of firefly flashes follows an inverse-square law, where the intensity (denoted as I) diminishes as the distance (r) from the light source increases. This relationship is mathematically represented as $I \propto 1 / r^2$. Additionally, light absorption by the surrounding air further reduces the brightness as the distance increases. As a result, firefly flashes are typically visible only over short distances, generally a few hundred meters at night, which is sufficient for communication between fireflies. The FA, introduced by Yang in 2008, was inspired by the light-emitting behavior of fireflies [17]. To streamline the algorithm's definition, three key assumptions were made:

- All fireflies are of a single sex and are naturally attracted to one another for mating purposes, regardless of gender.
- The attractiveness of a firefly is determined by its luminous intensity. When two fireflies interact, the one with lower luminosity is drawn toward the one with higher luminosity. The attraction strength is directly proportional to their luminous intensities, which diminish as the distance between them increases. If the luminous intensities of both fireflies are equal, their movement becomes random.
- The luminous intensity of a firefly is representative of the value of a target function.
- Two key factors must be considered in the FA: variations in luminous intensity and the formulation of attractiveness or deceptiveness. To streamline the algorithm, the absorption of fireflies can be based on their luminosity, which is determined by the target function.

For maximization problems, the luminosity I of a firefly at a specific position x can be considered as $I(x) \propto f(x)$, where f(x) represents the value of the target function. Although the attractiveness β is relative, it must be observed by other fireflies for their judgment. Therefore, this value may vary based on the distance r_{ij} between firefly i and firefly j. As the attractiveness of a firefly is influenced by the intensity of the flashes perceived by neighboring fireflies, the attractiveness β can be defined using Equation 1.

$$\beta = \beta_0 e^{-\gamma r^2} \quad (1)$$

The attractiveness parameter β_0 represents the attractiveness value at a distance of r=0, indicating the initial attractiveness between fireflies.

The distance between firefly i and firefly j, given their respective positions x_i and x_j, can be calculated using the Cartesian distance formula, as shown in Equation 2.

$$r_{ij} = x_i - x_j = \sqrt{\sum_{k=1}^{d}\left(x_{i,k} - x_{j,k}\right)^2} \qquad (2)$$

That $x_{i,k}$ is the K_{th} component of the coordinate distance of x_i of the i_{th} firefly. In two-dimensional problems, the value of the distance is calculated according to Equation 3.

$$r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \qquad (3)$$

(3)

The movement of firefly i towards a more attractive (brighter) firefly j can be defined using Equation 4:

$$x_i = x_i + \beta_0 e^{-\gamma r_{ij}^2}\left(x_j - x_i\right) + \alpha\, \epsilon_i \qquad (4)$$

Where β_0 is the attractiveness, α is the random generator parameter, and ϵ_i is the random vector of the numbers shown by a Gaussian distribution or a uniform distribution.

For most implementations, we can consider β_0 =1 and $\alpha \in$ [0,1]. In this formula, the parameter γ indicates the attractiveness changes, and its value is used in determining the convergence velocity and how the FA algorithm behaves. In theory, it is $\gamma \in [0, \infty)$.

In this section, we will explain the proposed method for improving energy consumption in the body area sensor network.

Two important aspects are considered in the FA: the clustering process and the routing mechanism. The proposed method introduces a clustering algorithm based on the FA for body area sensor networks. It utilizes factors such as residual energy, inter-cluster distance, and distance to the sink node to determine the CH. In this approach, both sensor nodes and the sink node are treated as fireflies. A virtual backbone is then formed using the CHs to simplify data routing, with the sink node, having the highest luminosity, acting as the root of this backbone.

The algorithm consists of two primary phases: clustering and routing. During the clustering phase, fireflies are grouped into separate clusters. Each firefly independently adjusts its timing before competing to become the CH. The scheduling of a sensor node i, represented as t(i), is determined using Equation 5.

$$t(i) = \frac{E_m(i) - E_r(i)}{E_m(i)} \times T_{CH} \qquad (5)$$

Where T_{CH} is the maximum time allotted for selecting the CH. $E_m(i)$ and $E_r(i)$ are the maximum initial energy and residual energy of i firefly, respectively. Also, the luminous intensity of I is considered according to Equation 6.

$$I \propto (\left(\frac{1}{r_{iS}^{2}}\right) + E_r(i) \qquad (6)$$

The algorithm uses Equation 6 to select the CH based on higher residual energy and a shorter distance to the sink node. A firefly with these characteristics is considered more attractive than others. After the scheduling process is completed, node i designates itself as the CH and broadcasts an introduction message within its transmission range R. The introduction message includes the node's ID, residual energy $E_r(i)$, and spatial information P(i). Upon receiving this message, firefly j withdraws from being a CH candidate, cancels its scheduling process, and functions as a normal node until the next round. Additionally, firefly j maintains a list, referred to as the Neighbor CHs Collection ($N_{Ch}(j)$

), which contains the fireflies that have been identified as CHs. In the subsequent rounds, firefly j determines its cluster membership using the information stored in $N_{Ch}(j)$. To form clusters, each normal node decides its membership by attempting to join one of the CHs listed in $N_{Ch}(j)$. Firefly j evaluates the attractiveness of the CHs in the $N_{Ch}(j)$ list using Equation 8.

$$\beta_{K,j} = E_r N_{Ch}(j) + \left(1/\left(r_{k,j}^{\ 2}\right)\right) \quad (7)$$

$$E_r N_{Ch}(j) = \frac{\sum_{k=1}^{m} E_r(v_k)}{m} \quad (8)$$

Where $\beta_{K,j}$ is the attractiveness of the CH k from the firefly j's point of view, $E_r N_{Ch}(j)$ is the average residual energy of the CHs in N_{Ch} (j) list of the j-th firefly, which is calculated according to Equation 8, $r_{k,j}$ is the distance of the jth firefly from the kth CH in the $N_{Ch}(j)$ list.

Regarding Equation 7, out of the CH fireflies in the $N_{ch}(j)$ list, the firefly j chooses a firefly as the CH, which is less distant from that CH and also has the most residual energy. Then, the firefly j joins the nearest CH, the remaining energy of which is greater than or equal to $E_r N_{ch}(j)$. Accordingly, clusters are formed.

In the data routing phase to the sink, a directed virtual backbone (DVB) rooted in the sink is created for all CHs. In the beginning, the sink node sends a message requesting the route to all the CHs in its 2R range. This message contains data such as node ID, level (L), and spatial information. It is considered that the sink node level is zero. Once the CH u receives a message, the node raises its level a little bit and chooses the sink node as its father PN (u) = sink. To explain, the level of all the CHs within the 3R sink range is 1. Similarly, the CH u sends a message requesting the route again to all the CHs within its range. The message contains information such as ID, L(u), $E_r(u)$, and spatial information P(u). If a CH v receives the message, and if its level is less than or equal to the node u level, it ignores that message. Otherwise, it increases the value of the level by one greater than the level of u and places it as a PN. In the same way, these steps will continue, and all the CHs will broadcast the message requesting the completion of the DVB creation process. A CH may have multiple PNs inside the DVB, so it will have multiple routes to the sink.

4. SIMULATION OF THE PROPOSED METHOD

4.1 Simulation environment

The effectiveness of the proposed approach was assessed using version 11.5 of the OPNET simulation tool. The primary aim of this simulation was to benchmark the performance of the proposed algorithm against the NODIC protocol. OPNET operates based on a hierarchical architecture comprising three integral layers: Network, Node, and Process. This structure enables visual modeling of WSN configurations and offers extensive customization of simulation settings. The platform facilitates in-depth performance analysis and comparison between different routing techniques. A comprehensive overview of the simulation parameters is outlined in Table 1.

Table. 1 Simulation Parameters

Parameter	Amount
The Way of Scattering Nodes in the Environment	Random
The Size of the Simulation Environment	10m × 10m× 10m
Type of Sending	CBR
Packet Size	1024 byte
Packet Rate	250kbps
Simulation Type	100 seconds
Mac Layer	IEEE802.15.6
The Initial Amount of Energy	200 joules
The Number of Sinks	1

The Number of Nodes	60
The Range of Radio Communication	1 meters
Packet Inter Arrival Time	Constant

The routing approach introduced in this work is tailored for healthcare monitoring systems. It operates under the assumption that all sensor nodes are within each other's communication range and are aware of their neighboring node positions. Central to the network is the sink node, which has superior processing and communication capabilities compared to ordinary sensor nodes and is primarily responsible for aggregating the collected data. As shown in Fig. 1, the architecture of the WBAN is presented in both its structural and operational forms according to the proposed method. Within this configuration, the sink node is positioned internally within the body, whereas the gateway node is placed in proximity to the patient or at another suitable location. Due to the impact of human movement, which can disrupt data collection, the sink node is designed to reliably gather information despite potential mobility-induced challenges. To assess the effectiveness of the proposed strategy, simulations were conducted on a network comprising 60 sensor nodes under three separate conditions. The first configuration distributes nodes randomly based on the IEEE 802.15.6 standard, known for offering 360-degree coverage, one-dimensional data support, low-power operation, cost efficiency, and real-time communication capability. The second configuration applies the FBC technique introduced in this study, where clusters are dynamically formed based on energy and proximity metrics. The third scenario employs the NODIC protocol, wherein data is relayed to the sink node via CH nodes. Importantly, the same network setup is maintained across all scenarios to ensure consistency and validity in comparative evaluation.

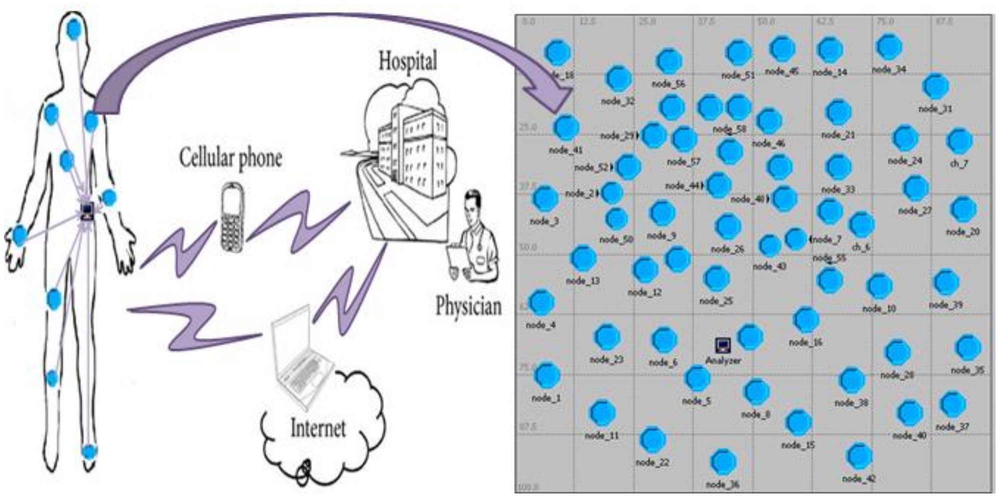

Fig. 1. Network Topology with 60 Sensor Nodes.

4.2 Simulation Results

Fig. 2 illustrates a comparison of average energy consumption among three approaches: the proposed algorithm, IEEE 802.15.6, and the NODIC protocol. The y-axis denotes the amount of energy consumed, while the x-axis corresponds to simulation time. Energy consumption here refers to the total energy spent by nodes for transmitting and receiving data, as well as their anticipated energy usage. Among the evaluated methods, the IEEE 802.15.6 protocol demonstrates the highest power consumption. This is primarily because its sub-nodes transmit data to the sink node without considering their residual energy, leading to inefficient use of resources. The NODIC protocol, on the other hand, selects CHs based on node location and the number of neighboring nodes with adequate energy reserves. However, in scenarios where suitable nodes are not found, it does not perform re-clustering. This can result in the selection of CHs with insufficient energy or few neighboring nodes in future rounds, accelerating energy depletion and destabilizing the network structure. In contrast, the proposed method leverages a FBC strategy that chooses CHs with higher remaining energy and closer proximity to the sink. Member nodes are grouped based on their distance to the selected CH, which significantly reduces the energy required for communication. This strategy not only conserves energy but also maintains effective data transfer across the network.

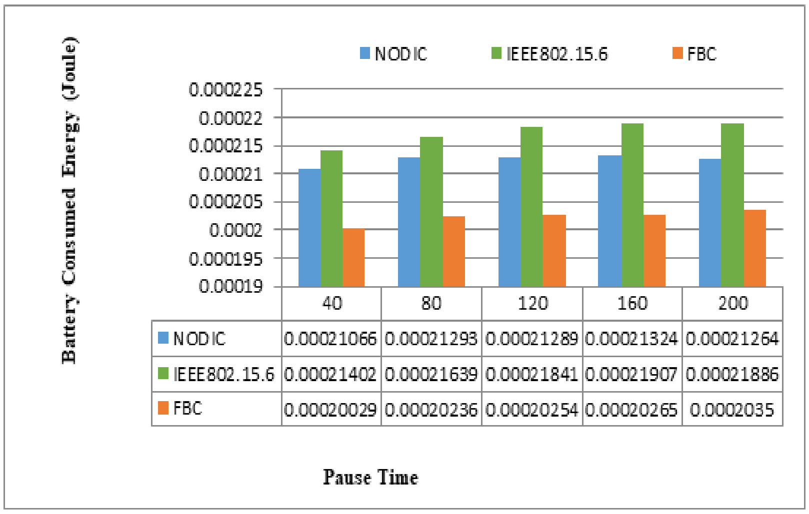

Fig. 2. Average Network Energy Consumption.

Fig. 3 compares end-to-end delays observed in three scenarios: the proposed method, the IEEE 802.15.6 protocol, and the NODIC protocol. The y-axis represents the time delay from source to destination, while the x-axis shows the simulation time. End-to-end delay is defined as the total time required for a data packet to travel from the source node to the sink. In the IEEE 802.15.6 protocol, increased delays are noted due to nodes initiating transmissions with insufficient energy, often leading to incomplete data delivery and communication disruptions. Likewise, in the NODIC approach, premature energy depletion of CH nodes hinders their ability to forward the collected data effectively, causing additional delay. On the other hand, the proposed algorithm achieves reduced end-to-end latency by assigning CH roles to nodes with higher residual energy and organizing member nodes based on their closeness to the CH. This strategy ensures smoother and more efficient data transmission, thereby lowering delay times in comparison to the other two protocols.

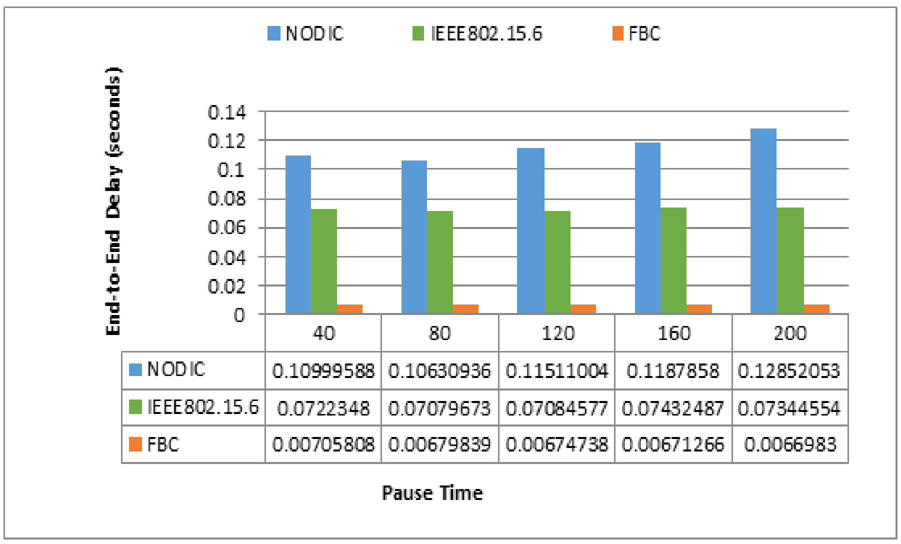

Fig. 3. End-to-end Delay.

Fig. 4 illustrates the likelihood of successful data delivery to the sink node under three different protocol conditions. The x-axis denotes the simulation time, while the y-axis reflects the calculated success rate of data transmission. This metric is obtained by dividing the amount of data correctly received at the sink by the total data volume transmitted at that moment, expressed in megabits per second. Analysis reveals that the IEEE 802.15.6 protocol demonstrates a lower packet delivery success rate compared to both the proposed and NODIC protocols. The lower performance of IEEE 802.15.6 is largely attributed to network congestion and the possible deactivation of nodes during operation. Conversely, the proposed algorithm prioritizes the selection of sensor nodes with greater residual energy for cluster formation. This ensures that the routing paths remain stable and functional throughout the communication process, thereby reducing the risk of premature node failure and maintaining data flow integrity. As a result, the number of packets that successfully reach the sink node is notably increased. The method's emphasis on stable, energy-efficient routing contributes directly to the improved reliability of data delivery.

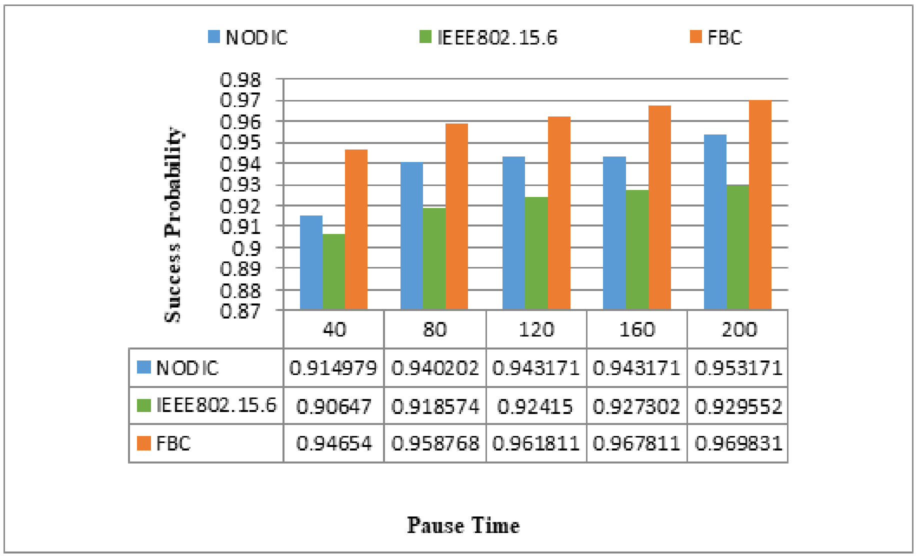

Fig. 4. The Probability of Success in Sending Information to the Sink Node

Fig. 5 illustrates the comparison of signal-to-noise ratio (SNR) performance among three approaches: the newly developed algorithm, the IEEE 802.15.6 protocol, and the NODIC protocol. The x-axis indicates simulation time, while the y-axis reflects the SNR values. SNR is a key metric that quantifies the ratio of the intended signal's strength to the level of background interference—where greater values signify better signal clarity. The chart shows that the IEEE 802.15.6 protocol consistently produces lower SNR values than both the proposed and NODIC methods. This reduction in SNR can be attributed to the protocol's tendency to rely on less reliable transmission paths, which may introduce bit-level errors and data corruption. Moreover, network congestion and instability associated with the IEEE 802.15.6 protocol exacerbate these issues by increasing noise and reducing the integrity of the transmitted signal. In contrast, the proposed method and NODIC protocol offer enhanced route stability and more reliable data delivery, which in turn lead to higher and more consistent SNR measurements.

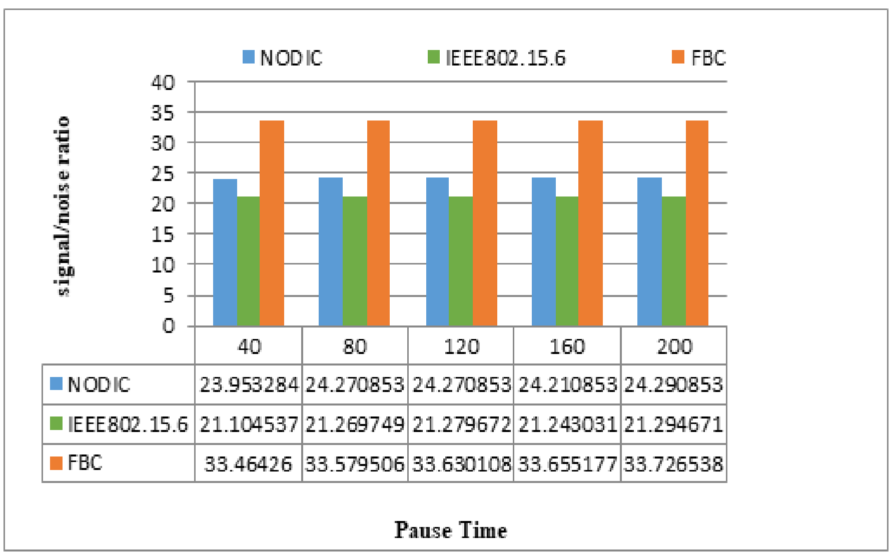

Fig. 5. Signal to Noise Ratio.

5. CONCLUSION

This research addresses the problem of excessive energy usage in body area sensor networks, which are widely used in diverse applications. To mitigate this issue, an innovative clustering technique based on the FA is introduced. The effectiveness of this technique was assessed through simulation experiments conducted using the OPNET simulator. Comparative evaluations were performed against the IEEE 802.15.6 standard and the NODIC protocol. Key performance indicators, including power consumption, end-to-end transmission delay, signal-to-noise ratio, and the likelihood of successful data delivery to the sink, were analyzed. The findings indicate that the proposed method achieved superior performance and improved packet delivery accuracy compared to both benchmark protocols. These enhancements are largely due to the algorithm's ability to select stable communication paths that prioritize nodes with higher residual energy. Additionally, the approach integrates both global and local optimization strategies, enabling it to efficiently escape local optima while maintaining a fast convergence rate. Overall, the FA demonstrated robust clustering performance by effectively utilizing both exploratory and exploitative search mechanisms.

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