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Improving network efficiency through data flow optimization techniques

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Abstract

The methods involve utilizing technologies designed to improve the flow of data and minimize the time taken to transmit information across the network has become vital. This study reviews the existing literature from multiple perspectives to improve data flow within networks, reduce latency, and ensure reliable communication for current applications and services. It focuses on improving different methods to increase the dependability of data transfer, reduce traffic overload, and elevate network performance. Furthermore, the research proposes an efficient approach for choosing forwarder nodes in Wireless Body Area Networks (WBANs), which relies on dual forwarder nodes instead of a single node. This method not only cuts down on energy usage but also extends the longevity and stability of the network while improving throughput. Furthermore, it investigates how the Dual Forwarder Selection and Strategic Network Performance Algorithm (DFSSNPA) may be modified to address critical challenges in WBANs. A comparison of the selection of energy-efficient forwarder nodes with prior studies. A full plan that gives priority to different ways of building network systems that are dependable, scalable, and efficient is necessary to satisfy the needs of today's data-driven society.

Keywords: Data flow optimization, Network performance, Energy-efficient forwarder node selection technique.

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تحسين كفاءة الشبكة من خلال تقنيات تحسين تدفق البيانات

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الخلاصة

الأساليب التي تنطوي على استخدام التقنيات المصممة لتحسين تدفق البيانات وتقليل الوقت المستغرق لنقل المعلومات عبر الشبكة لقد أصبح أمراً حيوياً. تستعرض هذه الدراسة الأدبيات الموجودة من وجهات نظر متعددة لتحسين تدفق البيانات داخل الشبكات، وتقليل زمن الوصول، وضمان اتصال موثوق للتطبيقات والخدمات الحالية. وتركز على تحسين الأساليب المختلفة لزيادة موثوقية نقل البيانات، وتقليل الحمل الزائد لحركة المرور، ورفع أداء الشبكة. إضافةً إلى ذلك، يقترح البحث نهجًا فعالًا لاختيار عقد إعادة التوجيه في شبكات منطقة الجسم اللاسلكية (WBANs). الذي يعتمد على عقد إعادة توجيه مزدوجة بدلاً من عقدة واحدة. لا تقلل هذه الطريقة من استخدام الطاقة فحسب، بل تعمل أيضًا على إطالة عمر الشبكة واستقرارها مع تحسين الإنتاجية. إضافةً إلى ذلك، فإنه يبحث في كيفية تعديل اختيار إعادة التوجيه المزدوج وخوارزمية أداء الشبكة الإستراتيجية (DFSSNPA) لمعالجة الأمور الحرجة في شبكات منطقة الجسم اللاسلكية (WBANs). وتقارن بين اختيار عقد إعادة التوجيه الموفرة للطاقة والدراسات السابقة. إن خِطَّة كاملة تعطي لطرق المختلفة لبناء أنظمة الشبكات التي يمكن الاعتماد عليها وقابلة للتطوير والفعالية ضرورية لتلبية احتياجات مجتمع اليوم الذي يعتمد على البيانات.

الكلمات الرئيسية: تحسين تدفق البيانات، أداء الشبكة، تقنية اختيار عقدة التوجيه الموفرة للطاقة.

1. Introduction

The effectiveness of network systems is critical in the modern world, where digital transformation and information technology have become essential to many industries. Ensuring the effective and seamless transfer of data across networks is vital, especially as data volumes continue to increase at an exponential rate. Improving network data flow is essential for enhancing overall performance,

http://www.doi.org/10.62341/tmio1129

reducing latency, and ensuring reliable communication, all of which are necessary for current apps and services to function properly [1]. The main goal of this study is to investigate the methods and approaches that optimize data flow in networks. It examines ways to increase network throughput, reduce congestion, and enhance data transmission reliability in general. Networks can be improved to meet the growing demands of real-time applications, cloud computing, and the Internet of Things (IoT) by utilizing cutting-edge strategies, including traffic engineering, congestion control, and adaptive routing protocols [2].

Data flow optimization is crucial for infrastructures at both the municipal and corporate levels, in addition to large networks. This study also will analyze the most recent developments in data flow management and propose efficient approach to improve network performance, focusing on reducing bottlenecks and increasing network resource utilization [3].

Data transmission bottlenecks, excessive latency, and network congestion have become recurring problems that impact the quality of service (QoS) for users and applications. Traditional network management techniques often struggle to keep up with the dynamic needs and rapidly growing data traffic on contemporary networks.

The issue stems from the current network infrastructure's inability to efficiently handle the massive and constantly increasing volume of data traffic. The growth of cloud computing, real-time applications, and the Internet of Things (IoT) has led to a surge in data sources, which has increased the strain on network resources. This makes it extremely challenging to maintain a reliable, high-performance network, where delays, packet losses, and inefficiencies can result in service interruptions, reduced customer satisfaction, and lost operational efficiency.

Traditional methods of optimizing data flow are often limited by their inability to dynamically adjust to changing network conditions. The unpredictable and diverse nature of contemporary data traffic can render traffic engineering and routing methods inadequate in certain situations. Therefore, to improve data flow, reduce congestion, and maximize network performance, cutting-edge technologies and solutions are urgently needed. Strategies must be developed to address this challenge, ensuring networks' scalability

http://www.doi.org/10.62341/tmio1129

and resilience as they evolve while simultaneously increasing data throughput.

In order to guarantee smooth communication and excellent user experiences in a world that is more linked, this study attempts to find and apply cutting-edge methods that can greatly increase data throughput, lessen congestion, and improve overall network dependability.

This research will highlight how to maximize network resources through the application of novel techniques in traffic engineering, adaptive routing, and congestion control. Finding efficient methods to control data flow will be essential to allowing the upcoming generation of apps and technology that drive our digital society as our reliance on high-speed, high-capacity networks increases.

2. Methodology

This study will adopt a quantitative research design, focusing on empirical data collection and analysis to evaluate various data flow optimization techniques and their impact on network efficiency. A broad overview of the literature was conducted to gain insights into the detailed examination of research efforts centered on methods for optimizing data flow and enhancing network efficiency. Analyzing data has been successfully applied to identify trends and insights regarding the practical applications of data flow optimization techniques in various network settings and to improve network performance in different sectors.

3. Literature review

3.1 Previous work

Researchers have completed a wide range of studies in this area. Several significant current research initiatives focus on data flow difficulties, maximizing network performance, innovative technology, and approaches for ensuring network scalability and resilience. Additionally, many writers have highlighted a number of challenges related to strategies for optimizing data flow. The authors of [4] carried out a thorough review of network flow applications, offering a short introduction to network traffic analysis, NetFlow, and sFlow. They addressed the cutting edge of network monitoring, analysis, administration, application categorization, user identification inference, and network security awareness. They discovered that network security continues to be a significant area

http://www.doi.org/10.62341/tmio1129

of study that covers many facets of the problem. In [5], the author made a number of novel technological recommendations to improve control quality and lower network nodes' buffer memory needs. In [6], the authors examined a computational model that is used in signal processing software environments in industry and experimentally in other settings. They gave this model, dataflow process networks, the name and analyzed its formal characteristics as well as its usefulness as a basis for the creation of programming languages. Authors in [7] consider a network model motivated particularly by blockchains and peer-to-peer live streaming. Data packet flows arrive at network nodes and need to be disseminated to all other nodes, relaying packets through the network via links of finite capacity. A packet leaves the network when it is disseminated to all nodes. They focus on two communication disciplines that determine the order in which packets are transmitted over each link, namely Random-Useful (RU) and Oldest-Useful (OU). They also provide other stability results and compare the performances of different disciplines in a symmetric system via simulation. Additionally, they study the cumulative delays experienced by a packet as it propagates through the symmetric system. Authors in [8] evaluate the practicality of realizing an ad hoc wireless network and investigate performance issues. Several mobile computers were enhanced with ad hoc routing capability and deployed in an outdoor environment, where communication performance associated with ad hoc communications was evaluated. These computers periodically send beacons to their neighbors to declare their presence. They examined the impact of varying packet sizes, beaconing intervals, and route hop counts on route discovery time, communication throughput, end-to-end delay, and packet loss. Authors in [9] evaluate network performance in terms of packet loss rate, delay, and throughput through simulation, considering two different channel models for on-body communication. A comparison with a WBAN based on the IEEE 802. 15.4 standard is also provided. In [10], the authors proposed a novel performance model for the IEEE 802. 11 WLAN is running in ad hoc mode. The model is built around providing the system with two one-dimensional state diagrams that can readily handle changes in a wide range of input parameters. The variables that were taken into account were the packet fragmentation factor, buffer size, and the

http://www.doi.org/10.62341/tmio1129

maximum permitted number of retransmissions. There are a number of other likely parameters of interest that the approach can handle. Throughput, latency, and the chance of delivery failure are the system performance indicators that were examined. The simulation findings from the IEEE 802. 15. 4 MAC protocol evaluations are presented by the authors of [11]. They examine the coexistence of IEEE 802. 11 and IEEE 802. 15. 4 the impact of these two wireless technologies on one another when they are in range and operating at the same time. In [12], the authors introduce a new energy-efficient, traffic-aware dynamic (TAD) MAC protocol for WBASN. The protocol depends on the dynamic modification of the wakeup interval in accordance with a traffic status register bank. The suggested approach enables the wake-up interval to converge to a stable state for both constant and changing traffic speeds, which leads to maximum energy efficiency. The authors in [13] introduced the evaluation of communication networks within a networked microgrid system using the User Datagram Protocol (UDP) and Transmission Control Protocol (TCP). The lifetime of a WBASN was predicted to be 36 times longer than that of other protocols. To guarantee the resilience of the created model using a network simulator (ns3), a comprehensive QoS analysis of the communication network has been provided under various traffic loads. In smart grids, the authors of [14] have used ns3 to create and test an SCN architecture. To demonstrate the dependability and resilience of the suggested network in fulfilling the smart grid communication requirements, a comprehensive design, modeling, validation, and performance evaluation are illustrated through numerous real-time experiments. Using the MATLAB/Simulink and OMNeT++ simulators, respectively, to simulate the dynamics of cyber-physical smart grids, authors in [15] have created a simulation platform that integrates power and communication networks. The Hypertext Transfer Protocol (HTTP) is used in the communication infrastructure for data transfer between the various MG components. However, the use of MATLAB/Simulink to represent the power system restricts the use of this platform in real-world situations because it does not support real-time implementation. The research presented in [16-18] emphasizes a significant research need in the analysis of the interdependence between communication networks and the performance of MG

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control. The suggested study emphasized stability and resilience in a variety of real-world situations, concentrating on the design, modeling, and quantitative analysis of communication infrastructure for different MG deployments. A novel protocol, dubbed Queue Utilization-Based RPL (QURPL), was put forth by the authors of [19] as a means of managing load balancing and preventing network congestion. In this protocol, each node chooses its root node based on hop distances and nearby nodes. The packet delivery ratio is greatly increased by QURPL. The RPL routing topology makes use of objective functions (OFs) to choose and improve routes. QURPL offers numerous benefits, including a longer network lifespan, higher performance, and reduced packet loss. The authors in [20] believed that Quality of Service (QoS) was a significant challenge and a difficult undertaking in assessing and selecting IoT devices, protocols, and services. They presented an intriguing distributed QoS selection methodology that relies on a multi-agent paradigm and a distributed constraint optimization challenge. Through a number of trials conducted in realistic distributed settings, this methodology was assessed. The applicability of IoT to environmental and agricultural regulations is another crucial factor. The authors in [21] evaluate the current state-of-the-art in proposed QoS approaches in IoT, specifically addressing: What layers of the IoT architecture have received the most research focus on QoS? What quality factors are considered by the quality approaches when measuring performance? What types of research have been conducted in this area? They have conducted a systematic mapping using several automated searches from the most relevant academic databases to address these questions. It also identifies various gaps in the research literature at specific layers of the IoT architecture. It highlights which quality factors and research contribution facets have been underutilized in the state of the art. Authors in [22] provide a trend of the future of the Internet of Things (IoT) in various aspects, encompassing all kinds of smart objects such as home appliances, actuators, smartphones, sensors, and RFID. Different types of wireless communication technologies are integrated within IoT. WSNs and WMNs are two of the most rapidly developing configurations in IoT. WSN consists of a set of small devices that route data to one or more sinks. In WMN, it acts as a gateway for WSN and other smart objects, providing fast

http://www.doi.org/10.62341/tmio1129

connectivity through the wireless medium and greater bandwidth than short-range communication systems such as Bluetooth and Zigbee. Authors in [23] seeks to investigate and use heuristic techniques as a method to maximize computer network performance. Heuristic algorithms, like genetic algorithms, ant colony optimization, and particle swarm optimization, provide flexible and effective methods for finding the best solutions to challenging problems that cannot be solved precisely in a realistic amount of time. The study uses simulations of various network scenarios to examine traffic management, network resource allocation, and best route selection. The simulation data demonstrate that, in comparison to traditional techniques, heuristic algorithms may boost throughput, decrease delay, and increase the efficiency of bandwidth utilization. Additionally, the algorithms used are capable of dynamically adapting to changes in topology and network conditions.

This research indicates that employing a dual-forwarder selection method with a strategic performance algorithm is crucial for Wireless Body Area Networks (WBANs). It addresses key issues such as energy efficiency, reliability, and network lifespan by introducing redundancy and dynamic optimization. It also shows how the DFSSNPA model provides a stronger solution by implementing a proactive dual-forwarder system. Utilizing redundancy along with a real-time performance algorithm not only enhances network lifespan and avoids hotspots, but also significantly boosts reliability and service quality.

3.2 Related Theory

3.2.1 Routing Protocols in Wireless Sensor Networks (WSNs)

WSN routing protocols can be categorized into several types. Depending on the network architecture, the first schemes in which nodes know their position and power are direct routing protocols (DRPs). Additionally, each node operates autonomously, recognizes an incident, and transmits its data directly to the base station in response. Because the available nodes are overhead-free regarding setup, it stands apart from other types of routing protocols. DRPs, in contrast to other routing protocols, require every node to be able to connect to and reach the base station; as a result, there is less network scalability since nodes in the farthest regions consume more energy than those closer to the base station [24].

http://www.doi.org/10.62341/tmio1129

Multi-hop routing protocols (MRPs), also referred to as flat routing protocols, are more powerful protocols that depend on network design. All nodes collaborate in MRPs to aggregate data and transmit it over several hops to the base station. The primary applications for these algorithms are data-centric scenarios, in which the base station requests data. Conducting a flooding operation, where each node broadcasts the sensed data until it reaches the base station, is one of the most critical aspects of deploying MRPs. Nodes consume more power due to the implosion caused by the high volume of duplicate packets received from various sources, even though it is simple to set up [25].

3.2.2 Machine learning and Detection System

Machine learning (ML) classifiers have significantly contributed to the development of intelligent systems across various fields. Over the years, machine learning techniques have gained popularity for identifying and detecting malware on both PC and mobile platforms. The research utilizes supervised machine learning, where a model is built and trained using the features discussed in the previous section that were sourced from a labeled dataset. The following machine learning techniques were considered in our investigation: the probabilistic naïve Bayes (NB), rule-based Bayesian network (BN), function-based J48, random tree (RT), and random forest (RF) machine learning classification algorithms [26].

3.2.3 Support-Based Permission Ranking (SPR)

As one of the technologies that helps networks become more efficient particularly in improving data flow by limiting access to resources and reducing the consequences of congestion or network failure support permission classification technology can manage and enhance data flow in networks. To further minimize the number of permissions, we must shift our attention to each permission's support. Generally, malware detection is not significantly affected by permissions with insufficient support. The permission requests from every app in the Android Manifest file are extracted to create the requested permission list. The permission data is converted into a binary format dataset, where a value of '1' indicates that the application has requested permission and a value of '0' indicates that it has not. An already comprehensive dataset for data analysis is formed by combining the permission lists from both malicious and

http://www.doi.org/10.62341/tmio1129

benign apps [27]. This technology allows resources to be distributed more effectively by classifying data or rights based on their function and importance in the network, ensuring that the most crucial data or permissions receive priority in the routing or processing process. In advanced data networks, such as 5G or cloud networks, permissions are established based on the level of support the data requires, enhancing data flow and reducing network latency or data loss [28].

3.2.4 Data Compression

Compression is the process of finding a more compact way to represent data to make it smaller. There are two primary forms of data compression: lossy, which permits a certain loss of image or signal quality to achieve better compression, and lossless, which ensures that the decompressed data is precisely the same as the source. Since every component of the message is necessary for accurate interpretation, we are primarily interested in lossless techniques for groupware communications. Only specific types of message data can be compressed using lossy techniques. Numerous lossless compression methods exist, which can be broadly divided into dictionary approaches and statistical models [29].

3.2.5 Groupware Network Performance

Refers to a collection of tools that enable the collective work group to collaborate over networks, including file sharing, group chats, email, and the performance required by the Groupware agreement regarding the speed at which data is transferred between users in a collaborative environment. A series of methods is used to achieve the quickest connection possible to enhance data flow in Groupware systems. Innovative methods for regularly streaming data from the network protocol to feedback transmission delays help minimize congestion, which is crucial for electronic systems that rely on real-time cooperation. The performance of real-time distributed groupware over real-world wide-area networks has been frequently criticized. These performance issues are primarily due to network challenges: latency, which is the time required for information to travel between locations; jitter, which is the variance in latency; and loss, which results from network packets not arriving at their destinations; and insufficient bandwidth. These challenges are common in today’s wide-area networks, and although networking

http://www.doi.org/10.62341/tmio1129

advancements aim to reduce these issues, they will persist for a while. Groupware programs must try to resolve these problems on their own in the interim [30].

3.2.6 Groupware Messaging

Information regarding state changes, data requests, instructions, and user event notifications must be exchanged between distributed groupware systems. Messages are packets of data transmitted across the network that include a single update, request, instruction, or notice. This communication occurs through messages, regardless of whether the underlying system utilizes distributed data structures, remote procedure calls, or a notification server, or if the model layers are replicated or centralized (as even centralized systems need to disseminate information about user actions and view changes). Groupware systems rely on messages [31].

There are several kinds of messages that might be used: model-layer updates, telepointers, text chat, system-level control and feedback messages, streaming multimedia like audio or video, and session-management messages are a few examples. Although the properties of many communication types vary, two major groupings can be distinguished. Streaming messages, which provide information on the current state of a user's activity or communication, are far more common than transactions, which deal with longer-term system changes, such as lock requests or changes to data structures. The distinction between multimedia and awareness messages is an important additional differentiation within the streaming message category. We are more interested in awareness messages (telepointers, avatar movements, intermediate object locations during drag operations, or changes to view locations) because video and VoIP transmissions are typically already compressed and handled with established protocols like RTP. Unlike transactions, streaming awareness messages have distinct QoS requirements. Specifically, while they do not all require guaranteed arrival, they necessitate low latency [32].

In reality, groupware programmers have to decide what should be sent and how. A groupware message must encapsulate several pieces of data and metadata: the message's sender (client ID), the message ID (for ordering and loss detection), and the application ID. (since many groupware programs can use the same network port to bypass firewalls). A timestamp is necessary to regulate buffer

http://www.doi.org/10.62341/tmio1129

playback. The type of communication (model update, telepointer motion) includes data values for every field name for every parameter (x position, y position). This information can be represented in several ways. Different representations offer distinct advantages, often at the expense of message size. However, the strengths of text, XML, and objects are significant enough that most groupware systems utilize these formats: text strings are used by GroupKit and Team Rooms; XML by Disciple; and serialized objects by JSDT (jsdt.dev.java.net/) and JAMM [33].

3.2.7 Energy-efficient Cloud Computing services over Core Networks

Cloud computing is already a widely recognized computing paradigm, and its significance is predicted to grow in the coming years. At the heart of cloud computing is virtualization, which enables the delivery, uninstallation, and management of desired services through the existing physical infrastructure, including servers, storage, and networks [34]. Our research studies the benefits of virtualization for energy efficiency, as well as the energy-efficient architecture of cloud computing services in core networks that optimize content distribution and virtual machine replication.

3.2.8 Energy-efficient forwarder node selection techniques

Energy-efficient forwarder node selection techniques are crucial for extending the lifespan of wireless sensor networks (WSNs) and other energy-constrained networks (like IoT devices, VANETs, etc.). The communication phase often consumes the most energy in these networks. [35]. Therefore, selecting the right nodes to forward data is paramount. Energy-efficient networking encompasses the design, implementation, and management of network infrastructures and protocols with the explicit aim of reducing the energy consumption of various network components, including routers, switches, servers, and wireless access points, all while upholding or enhancing performance and reliability. This strategic approach yields dual benefits: it significantly reduces operational costs for network operators and data centers, and it plays a crucial role in minimizing the environmental impact of IT infrastructure [36]. For resource-constrained network environments, such as Wireless Sensor Networks (WSNs), Internet of Things (IoT) networks, and

http://www.doi.org/10.62341/tmio1129

Mobile Ad-Hoc Networks (MANETs), the challenge of limited battery life is particularly acute. In these contexts, energy-efficient forwarder node selection is not merely beneficial but vital for prolonging network lifespan, preventing premature node failure, and maintaining overall network functionality, especially in remote or inaccessible deployments where battery replacement is impractical [37]. The transition from 5G to 6G, for instance, is anticipated to embed sustainability as a native attribute of the network, reflecting a profound shift in the communications industry's approach to environmental responsibility. Energy-efficient forwarder node selection is a multifaceted problem, often tackled by combining intelligent algorithms (heuristics, meta-heuristics, machine learning) with fundamental principles of energy conservation (load balancing, residual energy awareness, minimizing transmission power) within various network architectures (e.g., clustering). The choice of technique depends heavily on the specific application and network characteristics [38].

- **Key Metrics for Energy-Efficient Forwarder Node Selection**

The selection of an optimal forwarder node is not based on a single criterion but rather a composite evaluation of various parameters that collectively contribute to energy conservation and overall network health. This process is Inherently a multi-objective optimization problem, requiring a delicate balance between energy conservation and other critical network performance metrics such as latency, throughput, reliability, and security. Optimizing for one metric, such as minimizing energy per packet, can inadvertently lead to negative consequences for another, such as reducing overall network lifetime due to the creation of "hot spots" or increasing data transmission delays. A truly energy-efficient solution must therefore consider a composite cost function that holistically balances these competing objectives. This understanding highlights that the problem is not univariate; it is a complex optimization puzzle where solutions must navigate inherent trade-offs, often requiring composite metrics and adaptive strategies to achieve a balanced, sustainable network operation rather than merely minimizing one energy-related parameter. Table 1 illustrates the summary of key metrics for Energy-Efficient Forwarder Node Selection.

http://www.doi.org/10.62341/tmio1129

Table 1. key metrics frequently considered for Energy-Efficient Forwarder Node Selection

Metric Name	Description	Importance for Energy Efficiency	Examples of Use
Residual Energy (RE) / Battery Level	Remaining power in a node's battery	Prioritizes healthier nodes, balances load, extends network lifetime.	Used to select next hop, avoid "hot spots," or determine Cluster Head (CH) eligibility.
Hop Count/ Distance	Number of intermediate nodes to destination; physical distance.	Balances shortest path (latency) with energy cost per hop; favors shorter hops to reduce transmission power.	Used in composite cost functions; protocols may prefer routes with more, shorter hops.
Link Quality (LQ)	Reliability and strength of a communication link.	Reduces retransmissions and associated energy waste by selecting stable links.	Incorporated into routing metrics alongside energy and load.
Traffic Load / Queue Size	Current data volume being handled by a node; backlog of packets.	Prevents congestion and premature energy depletion of overloaded nodes by distributing traffic.	Used to select less burdened forwarders, influencing route stability.
Transmission Power Control	Adjusting radio power to minimum required for successful communication.	Directly minimizes active communication energy consumption.	Nodes dynamically adjust power based on receiver distance and link quality.
Node Mobility	Frequency and predictability of node movement.	Accounts for dynamic topology changes, avoids energy waste on broken routes.	Protocols adapt route discovery/maintenance to node movement patterns.

http://www.doi.org/10.62341/tmio1129

Trust Factor	Reliability and non-maliciousness of a node.	Prevents energy-draining attacks by malicious nodes and ensures data integrity.	Used in secure routing protocols to filter out untrustworthy forwarders.
Data Size / Redundancy	Volume of data transmitted; presence of duplicate information.	Minimizes energy spent on unnecessary transmissions and processing.	Data aggregation, compression, and event-driven reporting reduce data volume.
Sleep Scheduling / Duty Cycling	Alternating between active and low-power sleep states.	Reduces energy consumption during idle periods by turning off radios.	Nodes periodically wake up to check for data, then return to sleep.

- **Common Performance Metrics for Protocol Assessment**

Researchers use a variety of important metrics to thoroughly analyze the effectiveness of energy-efficient routing protocols:

- Total energy use, energy use per packet, and total energy utilization are all examples of ways to quantify the protocol's efficiency. Generally speaking, reduced usage suggests a more effective procedure.
- The operational life of the network is measured by this metric, which is frequently described as the period until the first node runs out of power, a specific number of nodes fail, or the network breaks up. Energy-efficient designs prioritize extending the lifespan of networks.
- The proportion of data packets that are successfully delivered from the source to the destination is measured by the Packet Delivery Ratio (PDR). A high PDR is a sign of dependable data transfer, which is essential for many uses.
- The throughput measures how well data is successfully sent over a communication channel. Increased throughput indicates greater network efficiency.
- The length of time it takes for a data packet to move from the source node to its ultimate destination is measured by latency or end-to-end delay. In real-time applications, delay minimization is essential.

http://www.doi.org/10.62341/tmio1129

- Overhead: This relates to the energy or bandwidth used by control packets that are needed for route discovery and maintenance, as opposed to the real transfer of data. A reduction in overhead suggests that the Protocol is operating more effectively.
- Reliability/Fault Tolerance: This measures the network's capacity to continue operating and communicating despite node failures, connection outages, or changes in topology.
- Scalability: This evaluates the protocol's capacity to effectively manage expanding node numbers and growing traffic loads without experiencing a corresponding rise in energy usage or a decline in performance.
- Quality of Service (QoS): QoS assesses the network's capacity to satisfy the unique data delivery requirements of an application, such as assured bandwidth, maximum delay, or tolerable packet loss.

The assessment of methods for choosing energy-efficient forwarder nodes highlights a crucial and developing area of network communication. Driven by the limited resources of network devices and critical environmental issues, energy efficiency is crucial for the sustainability, longevity, and high performance of contemporary wireless networks. Established methods, particularly hierarchical clustering and swarm intelligence, have provided basic solutions by intelligently optimizing data routes and balancing the energy load among network nodes. Notwithstanding these developments, major issues remain. The inherent resource limitations of network nodes, the complexities brought about by dynamic network topologies and node mobility, and the significant scalability challenges related to large-scale implementations are all included.

4. Proposed technique

4.1 Overview

This study presents a novel energy-efficient forwarder node selection technique based on dual forwarder nodes rather than a single forwarder node selection on-body in Wireless Body Area Networks (WBANs), addressing the issue of single forwarder node selection in WBANs. The network is divided into two logical groups, Group-A and Group-B, figure 1 illustrating how the nodes in Group-A and Group-B interact with each other and with the central coordinator/sink in a WBAN. A distinct forwarder node is

http://www.doi.org/10.62341/tmio1129

chosen from among the sensor nodes for each group, which are preprogrammed to be recognized as Group-A or Group-B nodes. The advantage of the proposed logical grouping is that sensor nodes designated for Group A transmit their data to the sink only through the Group A designated forwarder node. The logical grouping of sensor nodes occurs based on their position on the body rather than the number assigned to it. Similarly, sensor nodes designated for Group B use the Group B designated forwarder node to convey their data. This approach increases network longevity, stability period, and throughput while minimizing energy usage OMNeT++, can be used to design the network topology (Figure 1), with the aim of implementing dual forwarder nodes for enhanced energy efficiency, reliability, and capturing necessary test metrics, isolating results from other traffic measurements, as well as creating code that can adjust testing repetitions and measurement durations. In OMNeT++, throughput can be analyzed by assessing the entire quantity of data that the destination (nodes in Group A or Group B with the central coordinator/sink) has successfully received over time. By measuring the channel throughput by monitoring the packets sent via the transmission medium over time, throughput is measured separately in both directions for any pair of network interfaces communicating.

When a network, especially a WBAN is divided into two logical groups, it’s typically done to achieve specific objectives related to:

- Improved Efficiency: By organizing nodes, management and data flow can be optimized.
- Enhanced Reliability: Redundancy or distributed responsibilities can increase resilience.
- Better Scalability: Grouping can help manage larger numbers of nodes.
- Targeted Functionality: Different groups might have different roles or priorities.
- Energy Management: Distributing tasks across groups can help balance energy consumption.

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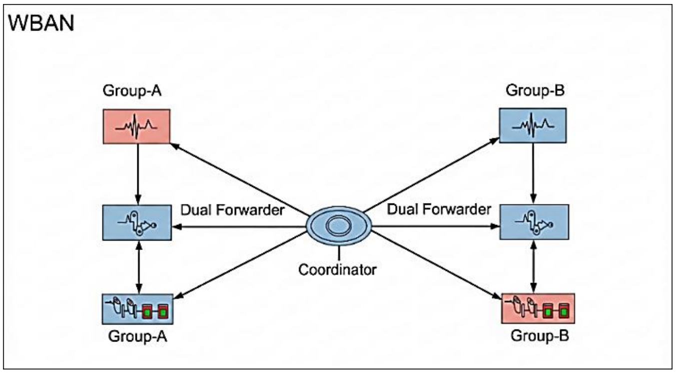

Figure 1. The interaction of the nodes in Group-A and Group-B with each other and with the central coordinator/sink

Figure 1 effectively shows a Star Topology WBAN, which is the most common and power-efficient design for many body area networks. All sensor nodes (from both Group-A and Group-B) communicate directly with the central coordinator, which acts as the data aggregator and gateway. Nodes within a group or between groups do not typically communicate directly with each other for data transmission. These interactions can be summarized as:

1. Sensor Nodes (in Group A/B) transmit to Their Group's Forwarder: Collect data and transmit it wirelessly to their designated Group-A or Group-B Forwarder.
2. Group-A Forwarder transmit to Group-B Forwarder (via Sink/Direct): Coordinate on load, status, and potential failover, often facilitated by the sink.
3. Group-A Forwarder transmit to Central Coordinator/Sink: Sends aggregated data from Group-A and its own status reports.
4. Group-B Forwarder transmit to Central Coordinator/Sink: Sends aggregated data from Group-B and its own status reports.
5. Central Coordinator/Sink transmit to Group-A/Group-B Forwarders: Sends control commands, routing instructions, and queries.

This structured interaction ensures that the advantages of dual forwarders (redundancy, load balancing, improved lifetime) are fully realized within the WBAN.

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- **The criteria for a node to belong to Group-A versus Group-B**

Given the context of a WBAN divided into two logical groups (Group-A and Group-B) with the aim of implementing dual forwarder nodes for enhanced energy efficiency and reliability. The criteria for assigning a node to either Group-A or Group-B are crucial for the effectiveness of the proposed architecture. Given the goal of improving energy efficiency and reliability with dual forwarders, the criteria would likely revolve around optimizing these aspects. The most common and logical criteria for assigning nodes to Group-A versus Group-B in such a setup is shows in table 2.

Table 2. The most common and logical criteria for assigning nodes to Group-A versus Group-B

Aspect	Concept	Criteria	Reasoning
Primary Criteria (Most Likely Candidates):			
Geographical Location / Body Segment	This is often the most fundamental way to create two distinct "logical" groups in a WBAN. Nodes are assigned based on which major body region they are attached to.	**Group-A:** Nodes located on one major half or segment of the body (e.g., all nodes on the **upper body** like chest, arms, neck, head). **Group-B:** Nodes located on the other major half or segment of the body (e.g., all nodes on the **lower body** like waist, legs, feet).	**Mitigate Body Shadowing:** By having forwarders in distinct body regions, the likelihood of *both* forwarders being simultaneously shadowed by the body is reduced. **Diverse Paths:** Provides two inherently different physical paths to the sink node (often placed at the waist or chest), increasing routing diversity **Natural Clustering:** Sensor nodes naturally cluster on different body parts.

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Distance to a Potential Forwarder / Sink	While location is primary, optimizing communication pathways plays a role	▪ Nodes that have a stronger and more stable link to a potential forwarder candidate in Group-A are assigned to Group-A. ▪ Nodes that have a stronger and more stable link to a potential forwarder candidate in Group-B are assigned to Group-B	Minimizes transmission power and improves link quality for individual sensor nodes to their assigned forwarder. This also influences which nodes are *candidates* for being a forwarder within their group
Secondary / Dynamic Criteria (Used for Forwarder *Selection* within Groups, or for Re-assignment)			
Residual Energy	To extend network lifetime, nodes with higher remaining battery life are preferred for forwarding roles	Within Group-A, the node with the highest residual energy might be chosen as the forwarder for Group-A. Similarly for Group-B	Prevents energy hotspots and balances energy consumption over time
Link Quality (RSSI/LQI/Packet Delivery Ratio)	Nodes with better communication links to the central coordinator (sink) are better candidates for forwarding	Within each group, the node that can establish the most reliable link to the sink, or to its neighboring sensor nodes, would be a strong candidate.	Ensures reliable data transmission and reduces retransmissions, saving energy.

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Traffic Load / Queue Status	To prevent congestion, a node currently handling a heavy load might be less desirable as a forwarder than a less busy one.	Nodes with smaller current data queues	Reduces latency and improves overall throughput
Mobility / Posture Stability (Advanced)	In highly dynamic WBANs, nodes on more stable body parts (less prone to rapid movement and shadowing) could be preferred	Using accelerometer data, identify nodes with lower recent movement variance.	Provides more stable communication paths over time

In summary, the criteria for assigning nodes to Group-A or Group-B should be tailored to the specific network and the goals of the analysis. The criteria can be based on network structure, node attributes, temporal patterns, or other relevant factors. Consider using a combination of these criteria to create a robust and meaningful grouping of nodes.

1.2 Strategic network performance

Several relevant viewpoints on network performance may be considered to inform this research, even though it acknowledges the paucity of studies focused on network-level performance [39]. When discussing strategic networks, performance is evaluated in terms of greater returns than what can be obtained alone or competitive advantages over non-participating enterprises. On the other hand, this perspective emphasizes organizational performance, especially for the controlling hub business, adopting a value creation viewpoint that highlights the value produced by joining the strategic network, surpassing what businesses can achieve independently. Although various performance metrics are employed and the empirical focus frequently lies on broader community effects, network performance has been thoroughly

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examined in public administration literature (Turrini, Cristofoli, and Frosini, for instance) [40]. Network-level performance evaluations include sustainability and viability, innovation and change, and the capacity to achieve stated goals. This study argues that perceptions of performance vary depending on the type and context of the network, as well as the different organizational and individual members, as previously mentioned. Assessing performance at the network level is challenging, as it raises the question, "Effectiveness for whom?" This suggests that the requirements of organizational actors and views on strategic network performance must align, although this is not always the case. The important network performance techniques and the direction of studies, along with a comparison of these techniques based on certain evaluation parameters, have been summarized in table 3 [41-42].
Regarding the efficacy of strategic networks, reaching the intended end, relative metrics of stakeholder outcomes, and the ability to create value gains are all examples of how successful a strategic network can be. Despite the many techniques available, there is ultimately no agreement on how to define or quantify network efficacy. Relevant perceptions of efficacy can also be influenced by other factors, such as the objectives or tasks of stakeholders, network members, or even the research framework. Network efficacy must be better understood outside particular contexts and should not be confused with metrics of organizational effectiveness [43]. Many ways exist to define effectiveness; we define it as the achievement of network objectives for the purpose of comprehending strategic network performance, while also acknowledging that goals may be emergent or adaptive. The connection between efficacy and efficiency must be clarified in order to comprehend strategic network performance. Others point out that There are trade-offs when seeking increases in efficiency or effectiveness, even if the article does not address whether such an interaction exists. At various organizational levels, different capabilities are needed for managing effectiveness versus efficiency, and the resource commitment required to achieve effectiveness somewhat limits high levels of efficiency [44]. Additionally, pursuing effectiveness can lead to inefficiencies (particularly in the short term) that make it challenging to attain high levels of both. This reflects the strategic tensions between

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efficiency, which can be achieved through greater flexibility, and effectiveness, which benefits from greater stability in developing a better understanding of these tensions [45].

Table 3. A comparison of network performance techniques

Aspect	Description	Benefits/Outcomes
Dual Forwarder Node Selection	The network is divided into two logical groups: Group-A and Group-B. Each group has its own designated forwarder node.	Increases network longevity, stability, and throughput, while reducing energy usage.
Data Flow Optimization	Dual transmitter selection technology is used to enhance data flow by selecting two devices for transmission based on proximity to the sensor or receiving stations.	Improves data flow, reduces congestion, lowers delays, and enhances network resilience, leading to better performance.
Backup Mechanism	By selecting two distinct devices for data transmission, the network ensures backup in case one device fails.	Increases reliability and reduces data loss by providing a backup in case of signal failure.
Energy Efficiency	Dual transmitter selection helps in selecting two transmitters based on factors like signal strength or proximity to optimize energy use.	Prolongs sensor device battery life and reduces the need for frequent recharging, enhancing energy efficiency.
Latency and Data Throughput	Reduces delays by distributing the load across two transmitters, decreasing strain on a single communication channel.	Increases data throughput and reduces latency, improving performance in time-sensitive applications like emergency or medical monitoring.
Network Dependability	The use of dual transmitters ensures that if one device experiences connection issues, the second device can still maintain communication.	Enhances communication continuity and reduces the risk of data loss.
Network Congestion	Reduces congestion by sharing the load between two transmitters.	Decreases congestion, leading to faster data flow and improved network performance.

http://www.doi.org/10.62341/tmio1129

Strategic Network Performance	Focuses on improving data flow, reducing delays, balancing loads, and enhancing Quality of Service (QoS).	Improves overall network performance, reducing transaction costs and enhancing resource coordination.
Sustainability & Viability	Evaluating network performance in terms of long-term sustainability, innovation, and the capacity to meet goals.	Helps to understand network efficiency and sustainability.
Strategic Network Efficiency	Achieving more with the resources available by reducing transaction costs, optimizing resource use, and improving integration and coordination.	Enhances flexibility, efficiency, and reduces operational costs.
Effectiveness vs. Efficiency	There are trade-offs between striving for efficiency (flexibility) and effectiveness (stability).	A better understanding of strategic network efficiency vs. effectiveness helps organizations balance stability and adaptability.
Network Efficacy	Network efficacy refers to achieving network objectives, which may evolve or adapt over time.	Understanding the relationship between network goals and overall performance helps organizations adapt and manage strategic tensions.

4.3 Dual Forwarder Selection and Strategic Network Performance Algorithm (DFSSNPA)

The Dual Forwarder Selection and Strategic Network Performance Algorithm (DFSSNPA) is a concept that can be adapted to solve critical problems in Wireless Body Area Networks (WBANs). WBANs, which consist of tiny sensors placed on or in the human body, are vital for real-time health monitoring, but they face unique and stringent challenges. The DFSSNPA framework, while originally conceived for larger-scale logistics, can be re-imagined to address the specific issues of WBANs, particularly energy consumption, reliability, and network lifetime. WBANs are highly resource-constrained and operate in a dynamic, often unpredictable environment. The key challenges are:

- **Limited Battery Life**: Most WBAN sensors are small, battery-powered, and often difficult or impossible to recharge or

http://www.doi.org/10.62341/tmio1129

replace (especially for implanted sensors). Energy efficiency is the single most critical factor for a WBAN's long-term viability.

- **Packet Loss and Reliability**: The human body can cause "body shadowing," where body movements or posture changes block the line-of-sight between sensors and the central coordinator (sink). This leads to unreliable data transmission, which is unacceptable for critical medical data.
- **Hotspot Problem**: Nodes closest to the sink often act as forwarders for other nodes. This high traffic load causes these "hotspot" nodes to deplete their energy much faster than others, leading to premature network failure.
- **Security and Privacy**: WBANs transmit sensitive patient data, making them vulnerable to security threats like data tampering and denial-of-service attacks.
- **Quality of Service (QoS)**: WBANs must be able to prioritize data. For instance, an emergency alert (e.g., from a heart rate sensor) must be delivered instantly, while a routine temperature reading can tolerate a slight delay.

The DFSSNPA framework can be tailored to WBANs by focusing its dual forwarder selection and strategic performance algorithm on the specific metrics and constraints of a body network.

1. **Dual Forwarder** Selection for Redundancy and Load Balancing: Instead of selecting two independent logistics forwarders, the WBAN adaptation of DFSSNPA selects two forwarder nodes within the body network.
2. **Primary Forwarder**: An algorithm selects a primary forwarder node based on a comprehensive cost function that considers its residual energy, distance to the sink, and current traffic load. This node handles most of the data forwarding for a cluster of sensors.
3. **Secondary Forwarder**: A backup forwarder is also selected. This secondary forwarder is chosen with similar criteria but is intentionally given a lighter load. Its role is to provide a reliable alternative and to prevent the primary forwarder from becoming a hotspot.
4. **Strategic** Network Performance Algorithm for WBANs: The strategic algorithm is the "brain" of the system, continuously

http://www.doi.org/10.62341/tmio1129

monitoring and optimizing the network in real-time. In a WBAN context, this algorithm would:

- **Real-time Performance Monitoring**: The algorithm continuously monitors the battery levels, signal strength, and data queue size of both the primary and secondary forwarders. It also tracks key QoS metrics like latency and packet delivery rate.
- **Dynamic Forwarder Re-selection**: The algorithm uses the monitored data to make intelligent decisions.
- **QoS-based Prioritization**: The algorithm can assign different priorities to different data types
- **Predictive Analysis**: More advanced versions of the algorithm could use machine learning to predict when a forwarder node might fail based on its historical energy consumption patterns and the user's activity levels. This allows the system to proactively reconfigure the network before a failure occurs, further enhancing reliability.

By implementing a dual-forwarder selection with a strategic performance algorithm, a WBAN can achieve a high degree of resilience, energy efficiency, and reliability, thereby solving the most pressing challenges of this critical technology. The framework shifts the network from a static, vulnerable system to a dynamic, self-optimizing, and long-lasting one [46].

- **How a DFSSNPA-like Approach Compares to Previous Works**

The DFSSNPA framework distinguishes itself from these previous works by introducing a fundamentally different paradigm: dynamic redundancy and strategic, real-time optimization, table 4 shows a direct comparison.

http://www.doi.org/10.62341/tmio1129

Table 4. The comparison of energy-efficient forwarder node selection with the previous works

Feature	Previous Works (Single- or Multi-Metric)	DFSSNPA (Adapted for WBANs)
Forwarder Selection	A single "best" forwarder is selected for each transmission based on a fixed or weighted cost function.	Two forwarders (primary and secondary) are selected. The primary handles the main traffic, while the secondary acts as a backup and a competitive benchmark.
Hotspot Prevention	Addressed by incorporating load-balancing metrics into the cost function, or by periodically shuffling forwarder roles. These methods are often reactive.	Proactively addressed by design. The secondary forwarder inherently offloads a portion of the traffic from the primary, preventing any single node from becoming a hotspot.
Network Reliability	Relies on the primary forwarder's link. A failure (due to body shadowing, interference, or battery depletion) often leads to packet loss and a delay while the network finds a new forwarder.	Enhanced by built-in redundancy. The secondary forwarder provides a pre-determined, ready-to-use alternative. If the primary's link quality degrades, the system can instantly switch to the secondary, ensuring uninterrupted data flow.
Optimization Strategy	Primarily static or reactive. The forwarder is chosen at the beginning of a transmission or when a problem is detected. The selection criteria are usually fixed.	Dynamic and strategic. The algorithm continuously monitors the real-time performance of *both* forwarders. It can intelligently re-route traffic based on a strategic performance algorithm that considers multiple variables and can even predict potential failures.
QoS Management	Some protocols include QoS as a metric in their cost function. For example, emergency data might use a single-	Integrated and dynamic QoS. The strategic algorithm can dynamically adjust the forwarding strategy based on data priority. For example, it might use the secondary forwarder as a high-

http://www.doi.org/10.62341/tmio1129

	hop, high-power transmission.	reliability, low-latency path for emergency data, while using the primary for routine data.

In summary: Energy-efficient forwarder node selection is a significant evolution from previous routing methods. While previous works often relied on a single, static metric like the shortest path, leading to unbalanced energy consumption and early node death, modern energy-efficient forwarder node selection uses a dynamic, multi-parameter approach to prolong network lifetime.

5. Results and discussion

These strategies involve utilizing technologies designed to improve the flow of data and minimize the time taken to transmit information across the network. Various techniques exist to boost network performance, each emphasizing a different aspect. They can be grouped and compared according to how they handle network traffic, infrastructure, and management. A comparison of these network performance methods, such as Dual Forwarder Node Selection and Strategic Network Performance, alongside factors like latency and data throughput, is shown in table 3. By facilitating data flow and minimizing congestion, which can degrade performance, these techniques enhance the overall efficiency of the network. The goal of these strategies is to enhance the overall effectiveness of the network by developing plans that improve how data flows throughout it. By aligning activities and resources, the aim is to create greater efficiency, which can reduce costs related to transactions and operations. In simpler terms, this means maximizing the return on the resources utilized. Key aspects of this include lowering transaction expenses, using network resources wisely, integrating and coordinating components, and assessing outputs against inputs. Increased efficiency, which brings flexibility, is considered one of the main advantages of networks compared to more rigid hierarchical setups. While previous research highlights the importance of considering network efficiency, there is a lack of practical studies evaluating which processes might influence it. Furthermore, this research indicates that employing a dual-forwarder selection method with a strategic performance algorithm is crucial for Wireless Body Area Networks (WBANs). It addresses key issues like energy efficiency, reliability, and network lifespan by introducing redundancy and dynamic optimization.

http://www.doi.org/10.62341/tmio1129

Unlike traditional approaches that depend on a single data path, this method actively manages resources to guarantee consistent, reliable, and energy-efficient data transmission. In the proposed structure, a WBAN can be categorized into two key groups: Group-A and Group-B, particularly when referring to dual forwarder nodes. This meet goals related to improved efficiency, better reliability, enhanced scalability, specific functions, and management. The DFSSNPA model provides a stronger solution by implementing a proactive dual-forwarder system. Utilizing redundancy along with a real-time performance algorithm not only enhances network lifespan and avoids hotspots but also significantly boosts reliability and service quality. This approach transforms network management from a basic reactive selection process into a complex, self-optimizing system. A comparison of energy-efficient forwarder node selection with previous methods is presented in table 4.

6. Conclusion

This document explores various tools and techniques for assessing network performance. Most empirical studies are built on simulation and measurement models. Due to the difficulties associated with measuring enterprise networks and the reliance on existing infrastructure for these assessments, much of the research has focused on how different operating system architectures affect network performance. No single tool stands out as the best for measuring network performance since each one is suited for particular scenarios. On the other hand, techniques aimed at optimizing data flow, like selecting dual forwarder nodes, can enhance network efficiency in Wireless Body Area Networks (WBANs). These strategies boost data throughput, reduce latency, and alleviate network congestion by making use of two separate transmitters for sending data, which is vital for time-sensitive tasks such as medical monitoring. Furthermore, these methods strengthen the network's resilience by providing backup options, ensuring steady communication even when one device fails. By enhancing network reliability and reducing data loss, these approaches contribute to more robust and dependable communication, which is crucial for maintaining network performance over time. Moreover, selecting two forwarders reduces the frequency of recharging, which is important for networks with limited energy. This approach

http://www.doi.org/10.62341/tmio1129

boosts resource usage, extends sensor battery life, and lowers energy use. The network is thoughtfully crafted to adapt to changing demands while ensuring sustainability and achieving its goals by focusing on optimizing data flow and minimizing delays, all while balancing effectiveness and efficiency. In summary, these strategies for data flow improvement not only boost the performance of wireless body area networks (WBANs) but also enhance the overall reliability, longevity, and efficiency of the network. This makes them crucial for the future of wireless communication technology. Although earlier studies have significantly advanced energy efficiency in WBANs using multi-metric cost functions and load-balancing methods, these often face limitations due to their reactive approaches and dependence on a single data path. The DFSSNPA framework presents a stronger solution by implementing a proactive dual-forwarder system. Utilizing redundancy and a tactical, real-time performance strategy, it not only extends the network's longevity and prevents areas of excess load but also greatly enhances network reliability and service quality. This Evolution shifts network management from a basic, reactive selection to a complex, self-optimizing system.

Recommendations

For future research, there is a need to conduct a study that offers a comprehensive method for evaluation by integrating various protocols and metrics and adopting a topology that reflects real-world networks.

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