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A Comprehensive Study of Multi-Criteria Routing Protocols in Intrabody Nanonetworks

Anass Khannous
ERMIA Research Team
National School of Applied Sciences (ENSAT)
Abdemalek Essaadi University
Tangier, Morocco

Anass Rghioui
Intelligent Systems and Sensor Networks (SIRC)
Hassania School of Public Works (EHTP)
Casablanca, Morocco

Said Bouchkaren
ERMIA Research Team
National School of Applied Sciences (ENSAT)
Abdemalek Essaadi University
Tangier, Morocco

ABSTRACT

This paper deals with intrabody nanonetworks and the importance of implementing effective routing protocols for these networks in healthcare systems. It evaluates the performance of multi-criteria routing protocols in intrabody nanonetworks by analyzing relevant research studies. The different studies are compared in terms of energy consumption, reliability, delay, and other criteria. The results show that certain routing protocols perform better than others depending on the selected criteria. Therefore, researchers must opt for the multi-criteria routing protocol that best matches their application.

General Terms

Nanonetworks Intrabody, Multi-criteria routing protocols

Keywords

Internet of Nano-things, IoNT, Applications Intrabody, e-health

1. INTRODUCTION

Research on intrabody nanonetworks began about a decade ago [3] and [4, 16]. However, the actual development and use of these networks have only recently begun to grow, due to the rapid growth in the miniaturization of technology and the improvement in the capabilities of wireless devices to operate inside the human body [6].

The origins of intrabody nanonetworks can be traced back to the late 1900s when there was significant progress made in the fields of microelectronics and biotechnology. In the beginning, research focused on the integration of implantable medical devices to treat various diseases, such as pacemakers. However, with the advancement of technology, researchers have begun to explore the possibilities of connecting these medical devices together to create networks of devices to implant inside the body [13].

Over the years, intrabody nanonetworks have experienced rapid growth in terms of processing capacity, communication range, energy, and shape factor. Numerous novel technologies have been created to enhance the functionality and efficacy of intrabody nanonetworks [6], such as new wireless communication protocols, new types of sensors, new materials, and new implant techniques.

Routing in a nanonetwork of nano nodes can be achieved in different ways, depending on the network topology and the application requirements [22]. In a grid network, each node is connected to neighboring nodes, and routing can be done deterministically using algorithms such as grid routing. In a ring network, nodes are connected in a circle, and data can be routed using ring routing algorithms.

In an ad hoc wireless network, nodes are not connected to a fixed infrastructure, and routing can be more complex. Routing algorithms for ad hoc networks include proactive approaches, which maintain an up-to-date routing table for each node, reactive approaches, which seek a path when a node needs to send data, and hybrid approaches, which combine aspects of proactive and reactive approaches.

Finally, in a hierarchical wireless sensor network, the nodes are grouped into clusters, and each of these clusters is overseen by a coordinating node. Routing can be done in a hierarchical fashion, using routing protocols such as Low-Energy Adaptive Clustering Hierarchy (LEACH) [15], which help minimize power consumption and maximize battery life of nanosensors.

Some of the commonly used routing protocols for intrabody nanonetworks include:

—Default Routing Protocol: These use a default routing approach to forwarding packets through network nodes.

—Multi-criteria routing protocol: this type of protocol makes it possible to take into account several criteria to choose the best route to transmit packets, such as quality of service, bandwidth, energy consumption, etc.

—Adaptive routing protocol: This kind of protocol uses a routing strategy that adapts to changing network conditions, such as topology changes or bandwidth variances.

—Hierarchical Routing Protocol: These are protocols that use a hierarchical structure to manage packets through the network, which improves the scalability and robustness of the network.

Multi-criteria routing protocol make it possible to take into account several criteria in the decision-making for the choice of the path to be taken to transmit the data [18]. These criteria can include the quality of the link, the level of network congestion, the energy consumption, the distance and other factors relevant to the network. A multi-criteria protocol has several advantages over other types of routing protocols, for the following reasons:

—Flexibility: They allow several criteria, such as bandwidth, distance, power consumption, reliability, etc., to be taken into account to determine the best route to transmit data.

—Robustness: These protocols can handle network failures by selecting alternate routes in the event of problems on the network.

—Quality of service: They can guarantee a specific quality of service for different types of traffic according to their selection criteria.

—Better resource utilization: They can efficiently use network resources, such as bandwidth and power, to improve network performance.

This study focuses on intrabody nanonetworks and emphasizes the significance of implementing efficient routing protocols for such networks in healthcare systems. It assesses the effectiveness of multicriteria routing protocols in intrabody nanonetworks by examining pertinent research studies. These studies are evaluated based on various criteria such as energy consumption, reliability, delay, and others. Another relevant point that was addressed in this study, is the challenges and opportunities associated with the use of multicriteria routing protocols in intrabody nanonetworks. The results and conclusions obtained from this comprehensive study provide suggestions for future research works on multicriteria routing protocols in intrabody nanonetworks.

The paper is structured as follows: Section 2 summarizes the different multicriteria routing protocols used in intrabody nanonetworks. A comparison of the different multicriteria routing protocols in terms of energy consumption, reliability, delay, etc. is detailed in section 3. Section 4 evaluates the performance of multicriteria routing protocols in intrabody nanonetworks through the studied approaches by highlighting the advantages and disadvantages of each protocol. In section 5, a discussion on the challenges and opportunities associated with the use of multicriteria routing protocols in intrabody nanonetworks has been presented. Finally, section 6 presents the conclusion and some recommendations for researchers.

2. LITERATURE REVIEW

Intrabody nanonetworks are a new area of research that focuses on the communication between nanoscale devices within the human body. These devices, also known as nanonodes, are capable of performing various tasks, such as drug delivery, sensing, and monitoring. However, the communication between these devices is a challenging task due to the complex environment of the human body. One of the critical issues in intrabody nanonetworks is to design efficient routing protocols to ensure reliable and timely delivery of data between nanonodes. In this state-of-the-art report, the existing routing protocols used in intrabody nanonetworkscare reviewed.

There are several routing protocols proposed in the literature that aim to address the challenges in intrabody nanonetworks. In the following, some of the most significant contributions will be summerized.

In the article [9], Balghusoon & al. discuss how Wireless Nano Sensor Networks (WNSN) and the Internet of Nano Things (IoNT) have emerged as new network paradigms, allowing for interconnectivity among nanonetworks and with other communication networks. Nonetheless, the creation of fresh network architectures and communication paradigms poses technical difficulties, particularly in routing protocols, which are essential for data and information transmission in WNSN and IoNT. This study provides an overview of current routing protocols to suit the limitations and characteristics of communication at the nanoscale, aiming to provide insights into WNSN and IoNT paradigms.

The survey of Yao & al. [22] analyzes and classifies existing routing protocols for Wireless NanoNetworks (WNNs) built on three fundamental principles: Node mobility, Network architecture and Routing path. Each type of routing protocol is described in detail, and their features are presented through a detailed comparison. Furthermore, the distinctive attributes of WNNs, such as the constrained resources and limited energy supply, are taken into account when examining the future research directions of routing techniques.

Abuali & al. article [1] discusses the challenges of communication in nanonetworks due to constraints in processing, storage, energy, and communication range capabilities of nanonodes. Multihop communication is currently seen as the solution for nanonetworks, and three routing protocols (controlled flooding, coordinate/routing for nanonetworks, and hierarchical ad hoc on demand distance vector) are evaluated based on energy consumption, network delay, transmission range, and network density.

Wang & al. [19] proposes a multi-hop deflection routing algorithm based on reinforcement learning (MDR-RL) for nanonetworks. Due to the extremely limited computational resources and transmission range of nanonodes, routing protocols in nanonetworks are very challenging to design. The MDR-RL algorithm uses new routing and deflection tables, and two feedback updating schemes based on reinforcement learning to dynamically explore routing paths during packet transmissions. Simulation results show that the MDR-RL algorithm can increase packet delivery ratio and decrease the packet average hop count.

Aliouat & al. [7] proposes a new routing protocol, termed as Multirelay to Multirelay Routing Protocol (M2MRPv2), has been developed for nanonetworks that are characterized by high local density and intense node instability. M2MRPv2 is unique in that it employs a proactive multirelay to multirelay routing mode, taking into account the residual energy level of the nanonodes and the reliability of the routing paths. Results demonstrate that the M2MRPv2 protocol significantly outperforms the Sustainable Longevity Routing (SLR) protocol in terms of transmission reliability and energy management.

Fahim & al. [12] proposes a routing protocol for Intrabody Nanonetworks (intrabody nanonetworks), which are composed of nanoscale devices implanted in the human body for physiological monitoring. The protocol integrates the Exponential Weighted Moving Average (EWMA) Based Opportunistic Data Transmission (ODT) and Artificial Colony Algorithm Based Query Response Transmission (ABC-QRT) approaches to efficiently handle the routing challenges of intrabody nanonetworks, such as lim-

ited energy resources and computational power. The simulation results demonstrate that the proposed protocol improves intrabody nanonetworks lifetime and reduces end-to-end delay compared to the flooding scheme.
Afsana & al. [2] discusses the development of electromagnetic communication at the nanoscale dedicated for body sensor networks (BSNs). The article suggests an enhanced performance plan for wireless body sensor networks (BSNs) utilizing nanocommunication over terahertz bands. This plan includes a new energy-saving forwarding method, a channel behavior model, and an energy model for energy harvesting and consumption. The proposed scheme was assessed for energy efficiency, outage capacity, and outage probability through the use of a nano-sim simulator. Results indicate that the proposed approach is effective in improving energy efficiency.
Xu & al. [20] proposes an energy balance clustering routing protocol (EBCR) for intra-body Wireless NanoSensor Networks (iWNSNs). The protocol adopts a hierarchical clustering method to reduce communication load and ensures successful data packet transmission while balancing energy consumption. The simulation results show that the EBCR protocol has advantages in prolonging network lifetime and ensuring data packet transmission success rate. The proposed protocol can be used as an effective routing scheme for iWNSNs.
Amjad & al. [8] proposes a new method of routing for biological nanonetworks is introduced in the paper, which utilizes a concentration gradient to direct the routing towards the sink. The routing technique capitalizes on bacteria's directional sensing and molecule prioritization to aid the transfer of information towards a sink node. The study conducts simulations to explore the properties of a multi-molecular field and the effectiveness of the proposed method. The results show that the proposed mechanism can achieve near-perfect delivery probabilities and maintain minimal propagation delays.
The paper of Tsioliaridou & al.[17] proposes a dynamic joint coordinate and routing system, called CORONA, for 2D ad-hoc nanonetworks. The system utilizes user-selected anchor-points to obtain a sense of geolocation for all nodes in the network. During the operation phase, the routing method utilizes a specific group of anchor nodes chosen by the packet sender, leading to a reduction in energy consumption and a decrease in packet loss and retransmission rates. The system requires minimal setup overhead and integer-based calculations only, making it simple and efficient for trustworthy operation.
In the paper of Bouchedjera & al. [11], the emergence of Software-Defined Metamaterials (SDMs) is discussed, which utilize embedded nanonetworks for constructing smart materials that can change their electromagnetic behavior. To enable future SDMs applications, energy-based data routing is crucial in highly lossy conditions that require path redundancy and the tiny storage capacity of nanodevices. The paper proposes a distributed cluster-based multi-hop point-to-point routing scheme for 2D dense homogeneous nanonetworks that target SDMs applications. The proposed scheme improves the energy efficiency and communication reliability and its performance is evaluated using the nano-sim tool on NS-3.
This paper [10] focuses on the Internet of NanoThings and the promising application of Software-Defined Metamaterials (SDMs) in smart materials. For static and dense 2D nanonetworks, the study suggests three iterations of a modified flood-based point-to-point routing system with the goal of increasing energy efficiency while retaining good communication reliability. Using the nano-sim tool on NS-3, the suggested schemes are thoroughly simulated under various performance circumstances, and the results demonstrate the advantages in terms of energy consumption, successful packet delivery ratio, and forwarding packet rate. To support future applications in the field, this work addresses the particular difficulties in nanonetworks, such as significant route loss and constrained data computing and storing capacities.
In [5], author presents a framework for data delivery in nano-scale networks, targeting green energy-efficient applications in the Internet of Nano Things (IoNT). The proposed framework utilizes nano-routers to relay data from a variety of nanonodes to a gateway connected to the Internet. Energy efficiency is considered in the routing process by taking into account the energy levels of the network and the hop count. Extensive simulations are conducted to demonstrate the effectiveness of the proposed approach compared to other energy-aware routing protocols. Results show that the proposed approach outperforms the baseline protocols in terms of network energy consumption and delivery success rate.
The authors of [14] present a Temperature-Aware routing protocol (TA-IBN) that addresses the thermal constraints of Intrabody Nanonetworks (IBN). The protocol aims to stabilize the temperature in the network, prevent temperature rise in heated regions, and avoid congestion. TA-IBN excludes data collection from hotspots areas, optimizes nanonodes' selection based on data freshness, and minimizes antenna radiation exposure time. The authors also demonstrate that the temperature increase analysis provided can be used for safety health assessment in medical applications. Extensive simulations using the Nano-SIM tool and comparison with the flooding scheme and Thermal-Aware Routing Algorithm (TARA) confirm that TA-IBN ensures safer intrabody routing and traffic distribution, normalizes temperature rise, avoids congestion, and reduces communication delay.
The authors of this article [21] present a three-layer vertical network structure for intrabody nanonetworks, consisting of nano nodes, nano routers, and a gateway. However, transmitting data through multiple hops in such a scenario is a challenge. To address this issue, the authors propose a flow-guided opportunistic routing (FGOR) protocol that improves throughput and reduces energy consumption in a single-flow environment where nano devices are restricted. The protocol uses a relative position (RP) model for candidate relay selection (CRS) and direction awareness to the gateway. A mobility gradient (MG) model is also proposed to redesign the CRS criterion, prioritizing candidate nodes based on node ID, available energy, and RP information. Simulation results show that the RP and MG models improve the throughput and extend the lifecycle of intrabody nanonetworks. The MG model performs better in terms of delay and successful transmission rate, especially within the circulation environment of intrabody.
Routing protocols commonly used for intrabody nanonetworks are variants of multi-criteria routing protocols, which consider criteria such as distance, energy cost, and link quality. However, all of these protocols may require adaptations to be used effectively in an intrabody nanonetwork due to the unique constraints such as low power consumption, low bandwidth, and transmission channel disturbances.

3. CRITERIA ROUTING PROTOCOLS

Multi-criteria routing protocols typically rely on multiple criteria to make routing decisions, such as:

—Routing with Centralized Control
—Distributed routing
—Task based routing
—Energy based routing

—Reliability based routing
—QoS-based routing
—Secure routing protocol
—Energy based routing
—Reliability based routing
—Time based routing

3.1 Centralized Control Routing

Routing with Centralized Control is a routing approach that involves some centralization in the routing decision. In this protocol, a centralized node, often referred to as a controller node, collects and analyzes network status information and decides the path for data packets to follow. This protocol uses several criteria, such as link quality, node load, and distance, to select the best path to transmit packets. A Centralized Control routing protocol offers better adaptability to dynamic network conditions compared to other centralized routing protocols, as it considers multiple criteria to make routing decisions. However, it requires higher resource consumption due to centralization and can also be more susceptible to errors and failures.

3.2 Distributed Routing

Distributed Routing is an approach to path determination where route computation is performed in a decentralized manner by each node in the network. In this protocol, each node collects information about direct neighbors and uses algorithms to evaluate different link quality criteria, such as distance, available bandwidth, transmission power, etc. The information obtained is used to select the best path to the destination. The advantage of this protocol is that it can be used to minimize different types of costs or constraints in intrabody nanonetworks, while allowing autonomous and decentralized operation.

3.3 Task-based

Task-based routing is a type of routing used to facilitate communication between different network nodes. It relies on the tasks or applications running on each node to determine the best route to take. When one of the nodes in the network needs to transmit data to another node, it determines the task running on that node and uses the TBR protocol to choose the most efficient route based on that task. This approach makes it possible to take into account the specific constraints linked to each task, such as the quantity of data to be transmitted, the available bandwidth and the duration of the transmission, to select the best route. A task-based protocol can improve communication efficiency in intrabody nanonetworks by optimizing route choice for each task, which can reduce transmission delays, improve reliability, and reduce power consumption.

3.4 Energy

Energy-based Routing uses the amount of energy available in network nodes to determine the best transmission path for data packets. In intrabody nanogrids, EBR is often used to conserve limited node power, improve battery life, and maximize network reliability. The most energetic nodes are used to transmit the data packets, while the less energetic nodes are kept for future use.

3.5 Reliability

Reliability-based Routing is used to select the most reliable transmission path for transferring data from one node to another. This protocol considers the reliability of nodes and links to determine the most appropriate path. RBR can be implemented centrally or distributed, depending on the needs of the application. In intrabody nanonetworks, reliability is a crucial factor because transmission errors can have serious consequences for the health of patients. The RBR therefore makes it possible to guarantee the quality of transmission of medical data and to optimize the performance of intrabody nanonetworks for medical applications.

3.6 Quality of Service (QoS)

QoS-based routing is used to optimize communication performance by considering different criteria such as bandwidth, latency, reliability, power consumption and security. This protocol helps ensure the quality of service required for critical applications such as real-time health monitoring and energy management. QoS-based routing can select the optimal path for data by using a weighting method to assess the quality of each path. QoS-based routing algorithms often use real-time information about network conditions to optimize communication performance.

3.7 Security

Security Based Routing (SRP) is used to ensure the security of data transmitted in the network. It can use techniques such as cryptography, identity verification and intrusion detection to ensure that only authorized nodes can access data transmitted through the network. SRP can also provide protection against attacks such as packet forgery and data modification, which ensures the reliability of data transmitted in the network.

3.8 Energy

This type of routing takes into account the energy consumption of the nodes in the network when selecting the transmission path. It chooses the transmission path that minimizes the overall power consumption of the network. While this may extend the battery life of nanosensors, it may cause increased transmission delay and decreased network reliability. Indeed, there may be situations where the transmission path chosen by EMC is not the most reliable or the fastest.

3.9 Reliability

This routing takes into account the reliability of the communication links when selecting the transmission channel. It chooses the transmission channel which has the lowest probability of packet loss. This can ensure reliable data transmission, but it may lead to increased node power consumption and transmission delay.

3.10 Time

This type of routing takes into account the transmission delay when selecting the transmission channel. It chooses the transmission path which minimizes the transmission delay. This can enable fast data transmission, but it can lead to the increased power consumption of nodes and decreased network reliability.

3.11 Hybrid Routing

It is possible to combine multiple routing protocol criteria in the same network using routing protocol merging algorithms. This approach makes it possible to use the advantages of each protocol to improve the performance of the network. However, the complexity of protocol merging can also increase, which can make the implementation and management of the network more difficult.

This kind of approach is often called "Hybrid Routing". For example, Energy-based routing can be combined with QoS-based routing to balance energy saving and QoS considerations. The Energy-based protocol can be used to select energy-efficient paths, while the QoS protocol can be used to guarantee a minimum quality of service for critical applications.
It is important to note that combining routing criteria can add complexity to the system and requires careful evaluation to determine if the advantages outweigh the disadvantages.
Multi-criteria routing protocols may be applicable to nanonetworks, but their adaptation depends on the specific characteristics and constraints of nanonetworks. Nanonetworks present unique challenges, such as limited processing capabilities, low power consumption, limited memory, and limited connectivity. These constraints can affect the performance and scalability of traditional routing protocols.
Thus, multi-criteria routing protocols for nanonetworks can be adapted to meet these constraints. For example, they can be designed to minimize power consumption by using short paths or optimizing next hop selection. Similarly, multi-criteria routing protocols can use heuristics to optimize the processing and storage performance of nodes in the network.
The adaptation of multi-criteria routing protocols will depend on the specific requirements of nanonetworks and the trade-offs between different performance criteria. Researchers continue to work on developing efficient routing protocols for nanonetworks to address these unique challenges.

4. WIRELESS TECHNOLOGIES AND MULTI-CRITERIA ROUTING PROTOCOLS

There are different multi-criteria routing protocols that can be used in intrabody nanonetworks. Each protocol has advantages and disadvantages in terms of power consumption, reliability, and delay.
The choice of the multi-criteria routing protocol partly depends on the wireless communication technology used. Different wireless technologies have different characteristics and limitations, and the selection of the wireless technology can affect the design and performance of the routing protocol. For example, some wireless technologies may have limited bandwidth or high error rates, which can affect the transmission delay and reliability of the data. Therefore, the multi-criteria routing protocol needs to consider these factors when making routing decisions.
The selection of the wireless technology can affect the design and performance of a multi-criteria routing protocol in intrabody nanonetworks. Different wireless technologies have different characteristics and limitations, such as limited bandwidth, high error rates, and energy consumption, that can impact the transmission delay, reliability, and energy efficiency of data transmission. Therefore, a multi-criteria routing protocol needs to take into account the characteristics and limitations of the wireless technology when making routing decisions.
For example, if a wireless technology has a limited bandwidth, the multi-criteria routing protocol needs to consider this factor when selecting a path for data transmission. The protocol needs to avoid congested routes and choose paths that can provide sufficient bandwidth for the data.
If a wireless technology has a high error rate, the multi-criteria routing protocol needs to consider the reliability of the data transmission when making routing decisions. The protocol needs to select paths that can provide error-correction mechanisms or avoid paths with high error rates.
If a wireless technology requires high energy consumption, the multi-criteria routing protocol needs to consider the energy efficiency of the data transmission when making routing decisions. The protocol needs to select paths that require less energy consumption or avoid paths that require high energy consumption.
Overall, the selection of the wireless technology can impact the design and performance of the multi-criteria routing protocol, and the protocol needs to consider the characteristics and limitations of the wireless technology when making routing decisions.
Intrabody devices can be used in combination with other wireless networks, such as cellular networks, to enable broader and more comprehensive communication. However, it can also lead to interference, packet collision, and network resource management issues. Multi-criteria routing protocols used in intrabody nanonetworks must therefore be designed to work in harmony with other wireless networks by avoiding interference and minimizing packet collisions. They must also be able to manage network resources efficiently to avoid bottlenecks and ensure smooth communication between different network nodes.
Additionally, multi-criteria routing protocols must be designed to adapt to changes in the network environment, such as changes in topology and interference from other wireless networks. They must also be able to handle packet loss and transmission delays caused by environmental disturbances.
Coexistence with other wireless networks represents a significant challenge for the use of multi-criteria routing protocols in intrabody nanonetworks, as it requires careful design of protocols to minimize interference, avoid packet collisions, manage network resources network and adapt to environmental changes.

5. DICUSSION

The use of multi-criteria routing protocols in intrabody nanonetworks indeed presents unique and complex challenges. Two significant challenges that arise in this context are the limited size of the sensors and their constrained power consumption, as well as the communication difficulties between network nodes within the human body.
Firstly, the limited size of the sensors in intrabody nanonetworks poses a challenge for implementing multi-criteria routing protocols. Due to their small form factor, these sensors have limited computational resources and processing power. Multi-criteria routing protocols typically involve complex calculations and require additional processing power to analyze routing information effectively. However, achieving such computational capabilities within the strict power constraints of intrabody nanonetworks becomes a difficult task. Consequently, there is a critical need to design routing protocols that are not only efficient in terms of computational complexity but also energy-efficient, ensuring optimal utilization of the limited power resources available.
Secondly, communication between network nodes in intrabody nanonetworks faces obstacles due to the nature of the human body. Radio signals, commonly used for wireless communication, can be significantly attenuated or blocked by body tissues. This can lead to a loss of connectivity between network nodes and hinder the establishment of reliable communication links. Additionally, the presence of other wireless devices within the body, such as pacemakers or implantable medical devices, can introduce interference that further complicates the communication process. Overcoming these challenges requires multi-criteria routing protocols that are robust and capable of adapting to the dynamic and unpredictable nature of signal propagation within the human body. Such protocols need to employ techniques to handle signal attenuation, interference, and

the potential presence of dead zones to ensure reliable communication pathways.
Addressing these challenges requires interdisciplinary efforts and innovative approaches. Researchers must focus on developing routing protocols that are specifically tailored for the unique constraints of intrabody nanonetworks. This involves exploring techniques such as energy-efficient algorithms, optimization strategies, and adaptive signal processing methods. Furthermore, considering alternative communication technologies, such as magnetic-based or acoustic-based communication, may offer solutions to mitigate the challenges associated with radio signal attenuation and interference.
The limited size and power consumption of sensors, as well as the communication difficulties within the human body, pose significant challenges for the use of multi-criteria routing protocols in intrabody nanonetworks. Efficient and energy-efficient routing protocols must be designed to overcome these challenges and ensure reliable and robust communication in such networks. Ongoing research and advancements in routing algorithms, signal processing techniques, and alternative communication technologies are crucial to enabling the successful implementation of multi-criteria routing protocols in intrabody nanonetworks.
Despite these challenges, the use of multi-criteria routing protocols in intrabody nanonetworks also presents opportunities. These protocols can enable more efficient use of power by optimizing transmission path selection and minimizing data loss. In addition, they can allow more accurate and real-time monitoring of physiological parameters, which can improve the diagnosis and treatment of certain diseases.
Moreover, multi-criteria routing protocols can enable more secure and reliable communication in intrabody nanonetworks, avoiding dead zones and ensuring that data is transmitted reliably and securely. This is particularly important for sensitive medical data that needs to be protected from unauthorized access.
To overcome these challenges and take advantage of the opportunities presented by multi-criteria routing protocols in intrabody nanonetworks, researchers must design routing protocols that are efficient, energy-efficient, reliable, and secure. One approach is to use machine learning algorithms to optimize the selection of the best transmission path and minimize power consumption. In addition, researchers can develop new communication technologies, such as magnetic-based communication, that are less affected by body tissues.
The use of multi-criteria routing protocols in intrabody nanonetworks presents both challenges and opportunities for healthcare. While the limited size and power consumption of intrabody nanonetwork sensors pose significant challenges, the use of efficient routing protocols can enable more accurate and real-time monitoring of physiological parameters, leading to improved diagnosis and treatment of chronic conditions. Furthermore, multi-criteria routing protocols can enable more secure and reliable communication in intrabody nanonetworks, ensuring the protection of sensitive medical data. To take full advantage of these opportunities, researchers must design efficient, energy-efficient, reliable, and secure routing protocols for intrabody nanonetworks.

6. CONCLUSION AND PERSPECTIVES

In conclusion, when it comes to choosing a multi-criteria routing protocol, it is crucial to consider the specific network and application requirements. Each protocol offers different advantages and trade-offs.
Power-based protocols are ideal for networks with energy-constrained nodes, as they prioritize extending the battery life of nodes. These protocols can significantly enhance network longevity by minimizing power consumption. However, they may sacrifice some reliability and speed in data transmission.
On the other hand, reliability-based protocols prioritize ensuring reliable data transmission. They employ robust mechanisms to minimize packet loss and guarantee data integrity. However, this focus on reliability often comes at the cost of increased node power consumption and transmission delays.
Time-based protocols, as the name suggests, prioritize fast data transmission. They are designed for time-sensitive applications where low latency is crucial. These protocols can achieve rapid data delivery, but at the expense of increased node power consumption and potentially reduced network reliability.
Ultimately, the choice of a multi-criteria routing protocol should align with the specific needs of the application. Researchers and network designers must carefully assess their requirements, considering factors such as energy constraints, reliability, and latency. By evaluating these criteria, they can select the protocol that best suits their application's unique demands.
Furthermore, it is essential for researchers to continue exploring and developing innovative routing protocols that strike a balance between power consumption, reliability, and speed. The field of network routing is constantly evolving, and new solutions may arise to address the challenges posed by different application scenarios.
In summary, the choice of a multi-criteria routing protocol depends on a thorough understanding of the network and application requirements. By carefully evaluating the trade-offs and considering factors such as power consumption, reliability, and latency, researchers can select the protocol that optimally meets their application's needs. Continued research and innovation will play a crucial role in further advancing multi-criteria routing protocols to meet the ever-evolving demands of modern networks.

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