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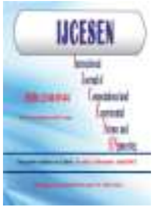

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Research Article

Qos-Aware Routing Protocols In Electromagnetic Nano-Networks: A Systematic Review

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Abstract:

Electromagnetic nano-networks, with their constrained resources and limited communication ranges, are emerging as key enablers in the Internet of Nano-Things (IoNT), spanning biomedical monitoring, environmental sensing, and industrial systems. Ensuring Quality of Service (QoS) in such networks poses significant challenges due to trade-offs among energy efficiency, latency, throughput, and data reliability. This study presents the first systematic literature review (SLR) that comprehensively examines the intersection of QoS and routing protocols in electromagnetic nano-networks. To emphasize the novelty and relevance of the survey, a rigorous SLR methodology was employed to systematically analyze all review papers in the literature from 2015 to 2025. Additionally, to maintain a focus on emerging advancements, the review exclusively targets routing protocols introduced between 2020 and 2025 that have not yet been addressed in prior surveys. Protocols are classified into three communication paradigms—Data-Centric, Peer-to-Peer, and Data Dissemination—forming a novel framework that aligns routing strategies with specific application domains and QoS expectations. The analysis reveals a predominant focus on energy conservation, with less emphasis on latency and throughput optimization, while security remains largely overlooked. Identified research gaps include computational complexity management, thermal regulation, and THz interference mitigation. The study underscores the need for multi-objective routing frameworks that balance QoS metrics and outlines future research directions emphasizing cross-layer optimization, predictive routing, and context-aware communication strategies tailored to the unique constraints of nano-networks.

1. Introduction

This Electromagnetic nano-networks are emerging as a transformative component of the Internet of Nano-Things (IoNT), integrating nanoscale devices with sensing, processing, and communication capabilities [1-4]. These networks hold significant potential for diverse applications, ranging from biomedical monitoring and environmental sensing to industrial control systems and defense operations [5-10]. Unlike conventional wireless networks, electromagnetic nano-networks operate within the terahertz (THz) band, enabling high data rates over extremely short distances. However, the intrinsic limitations of nanoscale devices — such as constrained energy reserves, limited memory, restricted processing capabilities, and short communication ranges — impose formidable challenges on the design and implementation of effective communication protocols [11-15].The complexity of electromagnetic nano-networks extends beyond the hardware constraints. Environmental factors such as molecular absorption and multipath fading in the THz band further exacerbate signal attenuation, leading to severe energy depletion and increased packet loss. Moreover, the ultra-dense deployment of nano-nodes intensifies interference risks, necessitating robust routing mechanisms that can adapt to dynamic network conditions while minimizing energy consumption [3, 16,17]. Consequently, ensuring optimal Quality of Service (QoS) in nano-networks, particularly in terms of latency, throughput, reliability, and energy efficiency, has become a critical area of research [18-20].

1.1. Background and Motivation

The advent of nanotechnology has facilitated the miniaturization of electronic components, giving rise to nano-nodes capable of performing sensing, computing, and communication tasks. These nodes are expected to operate autonomously or cooperatively to enable advanced applications in diverse domains [21-25]:

- **Biomedical Monitoring:** Intra-body nanosensor networks can monitor physiological parameters, detect early disease markers, and deliver targeted drug therapies, thereby enhancing patient care and treatment outcomes.
- **Environmental Sensing:** Deploying nano-nodes in environmental monitoring systems enables the detection of chemical pollutants, biohazards, and climatic changes at a molecular level, providing unprecedented precision and accuracy.
- **Industrial Control Systems:** Integrating nano-networks in industrial settings can facilitate real-time monitoring of structural integrity, equipment performance, and hazardous conditions, improving operational efficiency and safety.

Despite the promising applications, ensuring reliable communication in nano-networks is fraught with challenges. Nano-nodes operate under stringent power constraints, with limited energy harvesting capabilities, making energy efficiency a paramount concern. Additionally, the high propagation loss and molecular absorption in the THz band restrict the communication range to millimeters, necessitating the development of multi-hop routing protocols. The dense deployment of nano-nodes also raises interference risks, complicating data transmission and increasing the likelihood of packet collisions [17].Routing protocols are pivotal in managing these challenges, as they determine how data is propagated across nano-nodes to ensure timely and reliable delivery. However, existing routing strategies for nano-networks are primarily designed to optimize individual QoS metrics, such as energy efficiency or latency, while neglecting other critical aspects like data reliability and security. Furthermore, most existing protocols employ static routing strategies that are ill-suited for dynamic nano-networks characterized by node mobility and fluctuating channel conditions [26, 27].Given these challenges, a comprehensive systematic literature review (SLR) [28] is warranted to assess the current state of QoS-aware routing protocols for electromagnetic nano-networks. Such a review is crucial for identifying emerging trends, research gaps, and potential optimization strategies in nano-network routing. Furthermore, unlike previous studies that focus exclusively on specific metrics or application domains, this review adopts a holistic perspective, systematically analyzing contemporary routing protocols across multiple QoS dimensions and communication paradigms., the simplest approach is to use this template and insert headings and text into it as appropriate.

1.2. Related Work

We conducted a comprehensive search of the relevant literature following the PRISMA guidelines [29] to establish the need for a systematic review. To ensure an exhaustive search, we included all review papers and state-of-the-art studies rather than restricting the search to SLRs alone. Automated searches were performed using Google Scholar, a widely recognized electronic database that indexes publications from major scientific publishers such as IEEE, Elsevier, ACM, and Springer. The search queries used the exact keywords in Figure 2, adding the following terms and synonyms: '*state of the art*,' '*systematic literature review*,' '*survey*,' and '*systematic mapping*'.

Initially, 383 papers met the search criteria. The selection process detailed in Section 2, involved an initial filtering based on titles, followed by abstract evaluation, and a comprehensive full-text review, as illustrated in Figure 1. After removing duplicates, preprints and irrelevant studies, 13 papers remained for further analysis. Through the snowballing process [30], 15 additional studies were identified, bringing the total to 28 papers. Ultimately, thorough full paper review, only 4 final papers were selected for detailed analysis, as shown in Figure 1. Table 1 illustrates a summary of selected review studies.It is essential to note that none of the selected papers explicitly addressed QoS in electromagnetic nano-networking. Instead, they primarily examined networking protocols, a critical aspect of our study. Moreover, the focus of this review is strictly on electromagnetic nano communication, excluding molecular and other paradigms. Readers interested in molecular communication can refer to surveys from the literature [31-35]. Additionally, THz communication aspects such as graphene antennas,THz sources, and circuits/devices, though relevant, are beyond the scope of this work. Comprehensive surveys in these areas are available in the literature [2, 15, 36-40]. Lemic et al. [17] deliver a wide-ranging overview of THz-band nanocommunication and nanonetworking, addressing elements such as protocol stacks, channel modeling, antenna design, and simulation frameworks. They classify network protocols into forwarding/relaying methods and routing mechanisms, distinguishing between direct transmission and relay-based delivery, as well as one-to-many flooding versus one-to-one unicast routing across regular and irregular topologies. Although some QoS-related aspects like latency, reliability, and energy consumption are touched upon, particularly in the context of software-defined metamaterials and on-chip networks, the survey lacks structured evaluation or comparative analysis across protocols. Moreover, while claiming adherence to the SLR methodology, the study omits key methodological components such as research questions and statistical validation, reducing its transparency. The survey primarily focuses on early-stage research (2015–2020) and omits recent advancements such as SDN, AI, and mobility-aware protocols, reducing its relevance to current nano-network challenges.Saeed et al. [26] focus specifically on Terahertz (THz) communication for Body-Centric Networks (BCNs), particularly in biomedical contexts. The survey explores fundamental components including signal generation, noise models, channel modeling, and modulation techniques suitable for in-body and on-body nano-communication. It emphasizes the importance of energy efficiency, low electromagnetic interference, and secure data exchange in constrained environments like human tissue. The authors highlight single-path and multi-path routing trade-offs, noting that the latter improves reliability at the cost of higher energy consumption. However, the study offers limited comparative evaluation of routing protocols and omits an in-depth discussion of advanced routing strategies, protocol scalability, or QoS trade-offs, focusing instead on foundational aspects.Balghusoon et al. [41] classify routing protocols for Wireless Nanosensor Networks (WNSNs) and the Internet of Nano Things (IoNT) into six categories, including cluster-based, probabilistic-based, and wake-up-based approaches. Their review emphasizes the importance of energy efficiency due to the limited capabilities of nano-nodes and discusses integration with broader IoT and healthcare systems. Although QoS-related concerns such as energy use and network longevity are acknowledged, the study lacks a comprehensive evaluation of latency, reliability, or throughput. Furthermore, it does not explore modern trends like AI, SDN, or adaptive protocols.Yao et al. Yao et al. [27] survey routing techniques in Wireless Nanonetworks (WNNs), organizing protocols by network architecture, node mobility, and routing paths. They further classify multi-path approaches into LFA- and DIF-based methods. While the study evaluates energy efficiency and scalability, it neglects deeper investigation into other QoS dimensions such as latency and reliability. Additionally, it provides limited insight into security and omits recent innovations in nano-network routing.A cross all surveys none of them address Quality of Service (QoS) in nano-networking, which is a central focus of our study. Additionally, the reviewed networking protocols primarily reflect the early stages of nano-networking research and the absence of historical development or enhanced versions of these protocols, as well as recent advancements and emerging techniques such as Software-Defined Networking (SDN), artificial intelligence (AI), or machine learning (ML) approaches. These technologies are crucial for enhancing the flexibility, scalability, and optimization of modern nano-networks, yet they are not covered in the reviewed studies. Furthermore, none of the studies adhere to the Systematic Literature Review (SLR) methodology, which significantly impacts the transparency and reliability of their paper selection process.

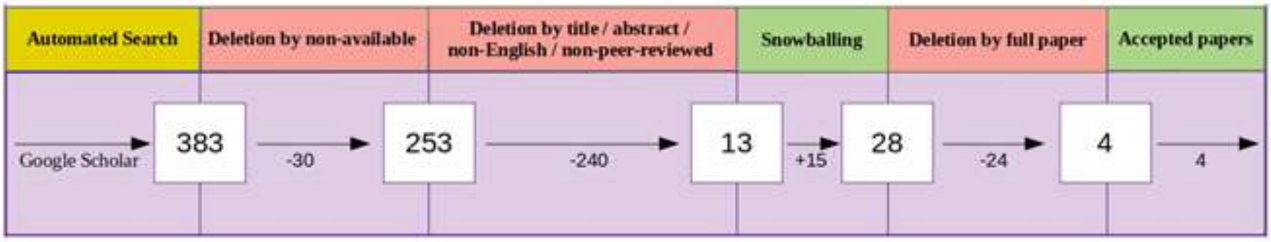


Figure 1. *Selection of the review papers*

Table 1. *The selected review papers*

Ref	Focus Area	N. of Routing protocols	Covered years	SLR	QoS
[17]	Examine THz nano communication and nano networking, focusing on key applications, protocols, channel models, and future research directions.	8	2015 - 2018	Not a typical SLR survey	NO
[26]	The potential of Terahertz communication technologies in body-centric networks, particularly focusing on energy-efficient communication protocols, healthcare applications, and their challenges.	10	2014 - 2020	NO	NO
[41]	Reviewing and classifying the routing protocols designed for Wireless Nanosensor Networks (WNSNs) and Internet of Nano Things (IoNT), while emphasizing their energy efficiency, the unique constraints of nanodevices, and the challenges associated with nanoscale communication.	25	2013 - 2018	NO	NO
[27]	Routing protocols for Wireless Nanonetworks (WNNs)	7	2014 - 2018	NO	NO
Our survey	Relation between routing protocols and QoS in electromagnetic nano-networks	25	2020-2025	YES	YES

As a result, the methodology used in these studies is unclear, making it difficult to assess the comprehensiveness and rigor of their literature review. Thus, this SLR addresses these gaps by systematically reviewing contemporary routing protocols (2020-2025), categorizing them into Data-Centric, Peer-to-Peer, and Data Dissemination paradigms, and evaluating them against multiple QoS metrics, including energy efficiency, latency, throughput, and security.

1.3. Research Questions and Objectives

This study aims to bridge the identified gaps by conducting the first systematic review that comprehensively examines QoS-aware routing protocols in electromagnetic nano-networks, focusing on protocols proposed between 2020 and 2025. The review is guided by the following research questions:

- **RQ1:** What are the contemporary routing protocols proposed for electromagnetic nano-networks, and how are they classified based on communication paradigms?
- **RQ2:** What are the key QoS metrics used to evaluate these protocols, and how do they perform in terms of these metrics?
- **RQ3:** What are the key challenges in designing and implementing QoS-aware routing protocols for nano-networks, and what future research directions can be proposed?

Addressing these research questions allows for a comprehensive evaluation of existing protocols, a critical analysis of their QoS optimization strategies, and a systematic identification of research gaps, laying a foundation for future protocol design.

1.4. Contributions of This Study

The primary contributions of this SLR are as follows:

- **Novel Classification Framework:** A novel classification framework is proposed, categorizing routing protocols into Data-Centric, Peer-to-Peer, and Data Dissemination communication modes. This framework not only organizes existing protocols but also aligns them with specific application domains and their corresponding QoS expectations.
- **Comprehensive QoS Analysis:** The study conducts a detailed comparative analysis of protocols across multiple QoS metrics, revealing critical trends in energy efficiency, latency, throughput, and data reliability.
- **Identification of Research Gaps:** The review systematically identifies key research challenges, including computational complexity, interference management, thermal regulation, and security, underscoring the need for multi-objective routing frameworks in nano-networks.
- **Future Research Directions:** Based on the findings, emerging research directions are proposed, emphasizing cross-layer optimization, AI-driven adaptive routing,

and hybrid communication frameworks to balance QoS requirements in dynamic, resource-constrained environments.

1.5. Paper Organization

The remainder of this paper is structured as follows: the next section presents the systematic review methodology, detailing the search strategy, inclusion/exclusion criteria, and data extraction process. Subsequently, in Section 3, the identified routing protocols are classified and analyzed according to the proposed taxonomy, with a detailed examination of their mechanisms and communication paradigms. Following this, Section 4 presents a comprehensive analysis of QoS metrics is provided, highlighting key performance trends and emerging optimization strategies in nano-network routing. The next Section 5 identifies critical challenges and proposes future research directions to address gaps in current protocol design. Finally, the conclusion synthesizes the key findings and outlines potential avenues for further research in QoS-aware routing for electromagnetic nano-networks.

2. Research Methodology

This study adopts the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to ensure a structured, transparent, and reproducible review process [29]. The PRISMA framework is employed to systematically identify, select, and evaluate relevant literature in the context of QoS-aware routing protocols for electromagnetic nano-networks. The methodology is structured into four main stages: search strategy, inclusion and exclusion criteria, data extraction and quality assessment, and review scope and categorization.

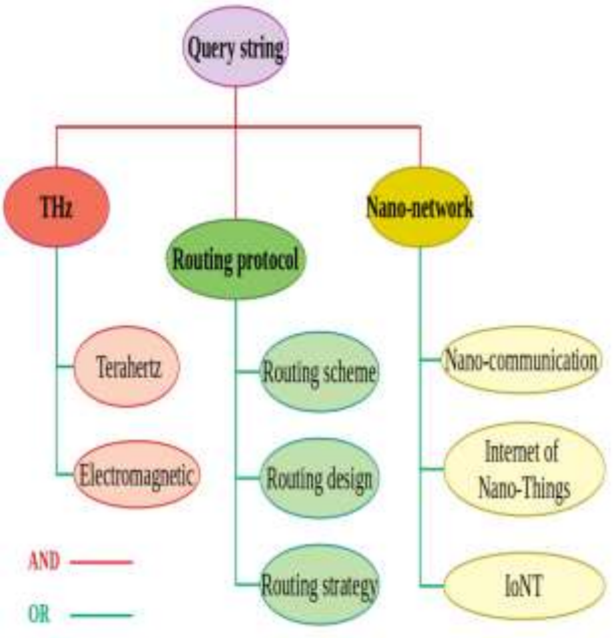
2.1. Search Strategy

The search strategy was designed to comprehensively cover relevant literature that proposed routing protocols for electromagnetic nano-networks. The electronic database utilized in this study is Google Scholar. The latter was chosen for their extensive coverage of peer-reviewed journals, conference proceedings, and technical reports. To ensure a comprehensive search, the following query string was composed using Boolean logic operators of AND and OR, were formulated based on the study's aforementioned research questions:

("routing protocol" OR "routing scheme" OR "routing design" OR "routing strategy") AND ("nano-communication" OR "nano-network" OR "Internet of Nano-Things" OR "IoNT") AND ("Terahertz" OR "THz" OR "electromagnetic")

Figure 2 shows the simple and sophisticated (using logical AND/OR operators) query strings. Additionally, to ensure full coverage of the relevant literature, combining automated database searches with a snowballing process [30].

Figure 2. *The search hierarchy shows the*



straightforward and mixed search terms

2.2 Inclusion and Exclusion Criteria

To maintain the relevance and quality of the reviewed literature, a set of predefined inclusion and exclusion criteria were applied during the selection process:

- **Inclusion Criteria:**
  - Research papers that propose routing protocols specifically in the context of electromagnetic nano-networks.
  - Studies published between 2020 and 2025
  - Peer-reviewed journal articles or conference papers
- **Exclusion Criteria:**
  - Papers focusing solely on acoustic, mechanical, and molecular communication
  - Studies that do not explicitly address routing protocols.
  - Duplicate studies, preprints, and non-peer-reviewed articles.
  - Non-available articles
  - Studies not published in English

After applying these criteria, the initial search yielded 251 research papers, which were further screened based on title and abstract relevance, and

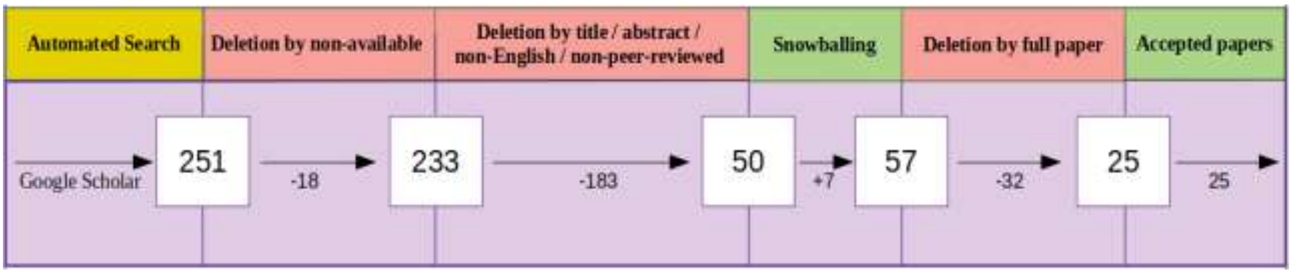


Figure 3. *Selection of the research papers*

not available leading to the exclusion of 362 papers. The remaining 50 papers. Through the snowballing process, where references from the selected papers were examined, 7 additional studies were identified, bringing the total to 57 paper**s.** Underwent full-text analysis, resulting in the final selection of 25 research papers that align with the research scope, as illustrated in Figure 3. In the next section, the selected studies were systematically categorized to align with the study's research objectives. Each protocol was further analyzed based on its QoS performance metrics, including energy consumption, latency, throughput, packet delivery ratio, and thermal regulation.

3. Analysis of Existing Routing Protocols

Routing in electromagnetic nano-networks presents significant challenges due to the extreme resource constraints, limited communication range, and dense node deployment inherent to these networks. Developing effective routing strategies is crucial to optimizing network performance while maintaining Quality of Service (QoS), particularly in terms of energy efficiency, reliability (PDR), latency, and throughput. To systematically analyze contemporary routing protocols and align them with the study's research objectives, we adopt a communication paradigm-based classification framework consisting of three primary classes, as illustrated in Figure 4:

- Data-Centric Communication
- Peer-to-Peer Communication
- Data-Dissemination Communication

3.1. Protocol Analysis

This classification framework is strategically structured to address **RQ1:** **"***What are the contemporary routing protocols proposed for electromagnetic nano-networks, and how are they classified based on communication paradigms*?**"** focusing on how each communication paradigm adopts distinct routing mechanisms to address specific QoS metrics. This structured approach not only facilitates a systematic analysis of protocol design but also highlights emerging trends and key design patterns that have not been previously categorized under such a framework in nano-network literature.

3.1.1. Data-Centric Communication

Protocols that prioritize data aggregation, query-driven dissemination, and event-based reporting to efficiently manage data flow from nano-nodes to a central sink or gateway. These protocols are further subdivided based on their data flow strategies:

3.1.1.1. Top-Down Communication Protocols (Query-Based, Command Dissemination):

Data is disseminated from a central controller to nano-nodes for targeted information retrieval or command execution.

1- Low Complexity Finite State Machine (LCFSM 2021) [42] reduces computational and memory overhead in nano-nodes through simple, deterministic routing. LCFSM uses a centralized controller to encode routing commands into binary sequences, which nano-nodes interpret using a lightweight finite state machine (FSM). Each node executes predefined actions like forwarding or waiting, based on its FSM state. Routing updates are sent periodically by the controller to adapt to network changes. The approach achieves very low complexity and fast execution, ideal for resource-constrained environments. However, its static nature limits adaptability to dynamic conditions, and its reliance on central control may introduce latency or bottlenecks.

3.1.1.2. Bottom-Up Communication Protocols (Event-Driven, Data Reporting):

Data is transmitted from nano-nodes to a central receiver or gateway based on specific events or sensed conditions, enabling event-driven data reporting. These schemes are further categorized based on their decision-making mechanisms into centralized and distributed approaches, each with distinct strategies for managing data flow and optimizing energy consumption.

1- Enhanced Energy-Efficient Algorithm (E3A 2020) [43] aims to balance energy efficiency and reliability in IoNT networks through adaptive

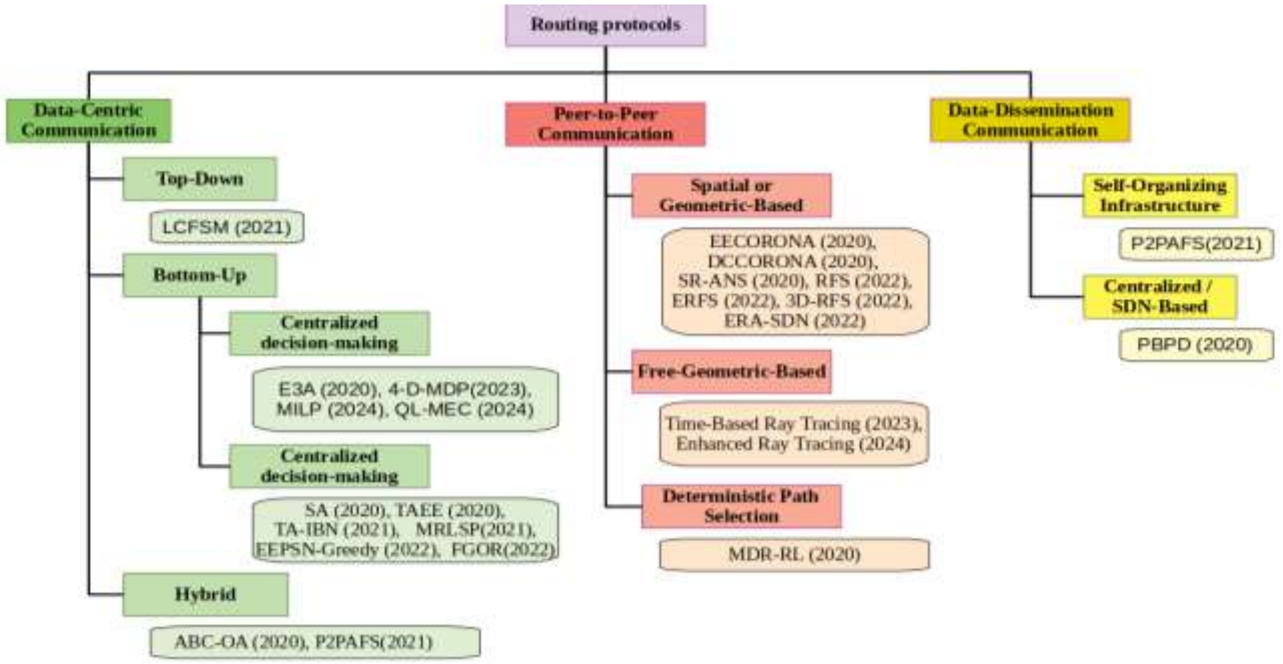


Figure 4. *Selection of the research papers.*

routing. E3A operates in a hierarchical structure using Cognitive Relay Nodes (CRNs), which perform reasoning based on energy and link metrics,learning from historical data to improve routing over time. Routing tables are updated dynamically to reflect both real-time and learned network behavior.

The protocol is adaptive and energy-aware, reducing unnecessary transmissions and improving reliability. However, learning-based updates introduce control overhead and may slow adaptation to sudden changes like node failures or energy drops.

2- Dynamic Multi-hop Routing using Markov Decision Process (4-DMDP 2023) [44] supports adaptive, flow-sensitive routing in mobile biomedical nano-networks. 4-DMDP models the network as a Markov Decision Process (MDP), with each node's state capturing parameters like location, energy, and data urgency. A centralized controller calculates optimal routing policies based on these states, then distributes a Q-table for decentralized execution. A two-hop strategy helps overcome range limitations. The protocol effectively adapts to mobility and flow dynamics, improving delivery in biomedical contexts. However, the MDP formulation is computationally intensive, and reliance on centralized state monitoring may affect scalability and responsiveness.

3- Mixed-Integer Linear Programming (MILP 2024) Routing Scheme [45] minimizes total energy consumption in nano-networks through centralized optimization of routing paths, bandwidth, and sub-band assignments. The MILP scheme gathers global network information—including node positions, energy levels, and sub-band availability—and formulates a Mixed-Integer Linear Programming (MILP) model at a centralized controller. This model computes optimal routing tables that define node paths, bandwidth allocation, and sub-band use, all while satisfying constraints related to interference and reliability. The resulting tables are distributed to nodes, which follow the fixed assignments without further local adaptation. This approach enables comprehensive, system-wide optimization with minimal processing burden on nano-nodes. However, the MILP's high computational complexity and reliance on centralized control limit its scalability and responsiveness, especially in dynamic or large-scale deployments.

4- QL-MEC 2024 (Reinforcement Learning for Multi-hop Energy Control**)** [46] adaptively manages energy-efficient routing in dynamic nano-network environments using reinforcement learning. QL-MEC employs a Q-learning algorithm to identify optimal routing paths based on real-time network state indicators such as energy levels, hop counts, and link quality. A centralized controller conducts the training phase by associating node states with actions and evaluating them through a reward function focused on energy efficiency and delivery success. Once the Q-table converges, it is distributed to nodes, which then make autonomous routing decisions based on local state and the learned global policy. The protocol enables adaptive, learning-based routing that responds effectively to changing network conditions. While it allows decentralized decision-making at runtime, the initial training phase is computationally intensive and relies on centralized infrastructure, which may affect scalability in larger or more volatile networks.

5- Temperature-Aware Intra-body Nano-networks (TA-IBN 2021 [47], TAEE 2020 [48], SA 2020 [49]) mitigate thermal effects during data transmission in biomedical nano-networks to ensure safe and reliable communication. These three protocols apply different strategies for thermal regulation. TAEE reduces redundant data transmissions through temporal data correlation, minimizing heat generation. SA (Simulated Annealing) selects routes based on a probabilistic model that considers node temperature history and data priority, optimizing for both thermal safety and delivery reliability. TA-IBN takes a simpler approach by excluding nodes that exceed a temperature threshold from routing decisions. In all cases, nodes make autonomous decisions using local temperature data to avoid thermal stress on surrounding tissues. Together, these protocols offer effective strategies for managing heat while maintaining delivery performance. Their decentralized design supports autonomy and adaptability. However, SA introduces computational overhead due to its probabilistic nature, and TA-IBN's deterministic exclusion mechanism may limit routing flexibility and scalability.

6- Multi-hop Routing Protocol Based on Link State Prediction (MRLSP 2021) [50] improves data delivery reliability and energy efficiency in intra-body nano-networks by predicting link stability and refining routing via fuzzy logic. MRLSP combines Kalman filtering and fuzzy logic to enable predictive, decentralized multi-hop routing. Nodes estimate link stability using a Kalman filter that analyzes real-time and historical signal data, then apply fuzzy logic to select next-hop nodes based on predicted link quality, residual energy, and distance to the Nano Controller (NC). Forwarding decisions are restricted to a geometrically defined candidate region to reduce redundant transmissions. The protocol also integrates ultrasonic energy harvesting, allowing energy-depleted nodes to recover and rejoin the network, thus extending network lifetime. MRLSP enhances routing reliability through link prediction and supports energy sustainability via harvesting. Its fully autonomous operation reduces control overhead. However, the protocol introduces high computational complexity and assumes static node positions, which may limit performance in mobile or dynamic biomedical environments.

7- Energy-Efficient Protocol for Sensor Networks (EEPSN-Greedy 2022) [51] prolongs network lifetime in nano-sensor networks through hierarchical, energy-aware, cluster-based routing. EEPSN-Greedy organizes nodes into clusters managed by nanorouters. During the Node Discovery phase, nodes share residual energy levels, and the node with the highest energy becomes the Cluster Controller (CC). A greedy algorithm is used to select next-hop nodes based on their proximity to the nanointerface and remaining energy. Within clusters, data is transmitted via single-hop to the CC, while inter-cluster communication follows a multi-hop structure through CCs. This approach prioritizes energy-rich nodes and limits transmission overhead through aggregation. The protocol is energy-efficient and reduces redundancy via cluster-based organization and smart forwarding. However, reliance on single-hop communication within clusters limits its effectiveness in sparse deployments, and cluster controllers may become hotspots, affecting long-term load balance.

8- Flow-Guided Opportunistic Routing (FGOR 2022**)** [52] improves data delivery reliability in mobile intra-body nano-networks by leveraging flow dynamics, such as blood flow, for guided packet forwarding. FGOR operates in a three-layer architecture with mobile nano-nodes, static nano-routers, and a central gateway. It uses two models: the Relative Position (RP) Model to estimate hop-based proximity to the gateway, and the Mobility Gradient (MG) Model to prioritize nodes moving toward the gateway. Nodes compute RP and MG indices locally from gateway probe packets, then select the next hop with the highest priority based on both indices. A backoff mechanism favors nodes closer to the gateway to reduce collisions and forwarding redundancy. The protocol effectively adapts to mobility and flow direction, enabling opportunistic multi-hop routing with improved delivery reliability. However, its performance depends heavily on accurate mobility estimation, and fluctuating flow conditions may introduce delays or misdirection in real-time forwarding.

3.1.1.3. Hybrid Communication Protocols

Combines top-down querying with bottom-up data reporting to support bidirectional data flow.

1- Artificial Bee Colony - Opportunistic Algorithm (ABC-OA 2020) [53] **e**nhances data delivery efficiency in dynamic, energy-limited nano-networks by combining data relevance filtering and swarm intelligence-based routing**.** ABC-OA operates in two phases. The first, EWMA-ODT, applies an Exponential Weighted Moving Average to suppress redundant transmissions by filtering similar physiological data. The second phase, ABC-QRT, leverages the Artificial Bee Colony algorithm to select optimal forwarders based on residual energy, data priority, and proximity. Nodes assume dynamic roles Scouts identify candidates, Workers evaluate fitness, and Soldiers perform the transmissions mimicking swarm behavior to balance energy use and data relevance. ABC-OA adapts well to network dynamics through intelligent, relevance-aware forwarding and reduces unnecessary transmissions. However, its reliance on primarily single-hop communication and the computational overhead of multi-criteria decision-making may limit performance in resource-constrained or highly mobile scenarios.

3.1.2. Peer-to-Peer Communication Protocols

Protocols that enable direct node-to-node communication through multi-hop routing, emphasizing reliable data delivery and adaptive path selection in dynamic network environments. These protocols can be categorized into two primary subcategories:

- Flood-Based Communication
- Deterministic Path Selection (No Flood-based)

3.1.2.1. Flood-Based Communication Protocols:

Nodes disseminate data by forwarding packets to multiple neighbors, leveraging either spatial/geometric constraints or probabilistic forwarding mechanisms.

1- Enhanced Energy-Efficient CORONA (EECORONA 2020) [54] improves energy efficiency and reduce transmission redundancy in CORONA-based nano-networks by introducing adaptive, energy-aware forwarding strategies. EECORONA extends the original CORONA protocol through three adaptive forwarding modes. Energy-Based Forwarding allows nodes to retransmit based on residual energy, while Counter-Based Forwarding limits retransmissions per packet to control redundancy. The Hybrid Forwarding approach combines both strategies to balance energy conservation with delivery reliability. Each node monitors its local energy level and adjusts its forwarding probability, dynamically tuning its behavior according to network density and reception feedback. The protocol effectively minimizes unnecessary transmissions and conserves energy while maintaining acceptable delivery ratios. Its adaptability to varying network conditions is a key strength. However, real-time energy monitoring introduces control overhead, and in sparse deployments, limiting retransmissions may lead to coverage gaps.

2- Distributed Cluster-Based Coordinate and Routing System (DCCORONA 2020) [55] enhances reliability and reduce redundancy in dense electromagnetic nano-networks through cluster-based, coordinate-driven routing. DCCORONA organizes nodes into logical clusters based on self-assigned virtual coordinates. Each cluster elects a Cluster Head (CH) using a randomized method that accounts for residual energy and link quality. Intra-cluster data is aggregated at the CH and forwarded hop-by-hop to adjacent CHs toward the destination. A counter-based forwarding mechanism reduces redundant transmissions within clusters, while a rollback mechanism ensures reliability by enabling retransmissions if acknowledgments are not received. Fallback nodes step in when CHs are unavailable, maintaining connectivity and preventing the “die-out” problem. DCCORONA effectively reduces energy consumption and redundancy through cluster coordination and selective forwarding. Its rollback and fallback mechanisms enhance reliability in sparse or lossy conditions. However, additional control overhead for clustering and CH elections, along with scalability challenges in highly dynamic networks, may affect performance in mobile or large-scale deployments.

3- Scaling up Routing in Nanonetworks with Asynchronous Node Sleeping (SR-ANS 2020) [56] reduces energy consumption and mitigate congestion in ultra-dense nano-networks through decentralized sleep scheduling and stateless routing. SR-ANS integrates asynchronous sleep scheduling with the Stateless Linear-path Routing (SLR) protocol. Nodes independently manage sleep-wake cycles based on local density and traffic, ensuring enough active neighbors to maintain connectivity. Packet forwarding follows the SLR approach using virtual coordinates, while probabilistic forwarding decisions based on residual energy and network density help prevent redundant transmissions. If a packet encounters a sleeping node, it is buffered until the node wakes or an alternate path is found. The protocol effectively conserves energy and reduces collisions using adaptive sleep and probabilistic forwarding, with minimal routing overhead due to stateless operation. However, delivery delays can occur if destination nodes are asleep, and scalability may suffer in sparse networks or during high traffic, where buffering risks memory overflow.

4- Efficient Retransmission Algorithm for Ensuring Packet Delivery to Sleeping Destination Node (ERA-SDN 2022) [57] enhances packet delivery reliability in nano-networks with asynchronously sleeping nodes using a selective, probabilistic retransmission strategy. ERA-SDN avoids full-scale retransmissions by selecting a subset of nodes in the destination zone to perform retransmissions based on their wake probability—calculated as the inverse of average sleep duration. Higher-probability nodes are prioritized, with staggered backoff timers managing the retransmission order. If one retransmission fails, the next node in the sequence attempts delivery, forming a cascading retransmission pattern. The protocol improves delivery reliability while conserving energy and reducing collisions by targeting retransmissions only to likely awake nodes. However, maintaining accurate sleep-wake profiles introduces control overhead, and delivery can be delayed in sparse networks or when sleep behavior varies under dynamic conditions.

5- Ring-Based Forwarder Selection (RFS 2022 [58], ERFS 2022 [59], 3D-RFS 2022 [60]) reduce redundant transmissions in ultra-dense nano-networks by spatially constraining forwarder eligibility using ring-based regions. These protocols define forwarding zones based on node position and transmission power. RFS uses concentric rings around the transmitter, allowing only nodes within a specific power range to forward packets. ERFS improves upon this by introducing overlapping rings, reducing redundancy further by limiting eligibility to nodes within multiple rings. 3D-RFS adapts the model to three-dimensional environments using spherical shells, enabling spatial control in varied topologies. Forwarding decisions are made locally based on received signal strength and ring boundaries. The protocols offer efficient, scalable control of retransmissions in dense environments through spatial filtering. However, they depend on precise power calibration and may suffer from increased complexity in 3D deployments. In sparse areas, strict spatial constraints can introduce forwarding delays.

6- Time-Based Ray Tracing (TBRT 2023) [61] and Enhanced Ray Tracing (ERT 2024) [62] enable coordinate-free, timing-driven forwarding to minimize redundant transmissions in dense nano-networks. TBRT uses packet reception timing from Time Spread On-Off Keying (TS-OOK) modulation to guide forwarding decisions. A node forwards only if it receives two identical bits from different upstream nodes in the same time slot, indicating alignment with the prior transmission path. ERT enhances this by introducing a control packet handshake (RTF, CTF, FORGET) to confirm forwarding eligibility and address propagation issues like signal overlap and path deviation. These protocols offer a low-overhead, coordinate-free approach ideal for dense deployments. TBRT is efficient and simple, while ERT adds robustness through controlled handshakes. However, both rely on precise synchronization and are sensitive to multipath effects, limiting their scalability in dynamic or noisy environments.

3.1.2.2. Deterministic Path Selection Protocols (No Flood-based)

Nodes select a specific path based on pre-defined criteria, such as shortest path, link quality, or energy availability, enabling structured communication with minimal redundancy.

1- Multi-Hop Deflection Routing with RL (MDR-RL 2020) [63] improves data delivery reliability in bufferless, energy-harvesting nano-networks using reinforcement learning to manage both primary and deflection routing. MDR-RL utilizes Q-learning to guide routing decisions. Each node maintains a primary Q-table for standard forwarding and a deflection table for alternate routes when failures occur due to node depletion, buffer overflow, or link issues. Routing actions are rewarded based on link quality, energy usage, and deflection effectiveness. Nodes learn optimal paths over time, dynamically adjusting both primary and fallback strategies to sustain reliable delivery in challenging environments. The protocol enhances reliability through adaptive, learning-based routing and ensures delivery continuity via deflection mechanisms. However, it introduces significant computational overhead and energy demands during training, with possible delays during route updates.

3.1.3. Data-Dissemination Communication

Protocols primarily designed to disseminate data propagation across the network. The protocols in this category can be further classified based on their organizational structure, including self-organizing infrastructures where nodes autonomously determine their forwarding roles, and centralized frameworks that rely on external controllers for path selection and data coordination.

3.1.3.1. Self-Organizing Infrastructure

1- Peer-to-Peer Addressing and Flooding System (P2PAFS 2021) [64] delivers a stateless, adaptive routing framework for dense nano-networks through self-assigned geo-addressing and dynamic forwarder selection across multiple communication modes. P2PAFS uses a Dynamic Infrastructure (DIF) model, where nodes autonomously classify themselves as forwarders or passive listeners based on real-time packet reception and network density. It supports multiple modes: data-centric (event-driven reporting), peer-to-peer (neighbor-based geo-addressing), and data dissemination (controlled flooding). A counter-based flooding mechanism limits retransmissions by prioritizing nodes with stronger reception, reducing redundancy while maintaining delivery reliability.

The protocol is versatile, stateless, and energy-efficient, supporting a wide range of communication scenarios. Its adaptive forwarder selection mechanism enhances scalability in dense deployments. However, performance may degrade in sparse networks or under fluctuating reception conditions, and dense environments may introduce reclassification overhead. 3.1.3.2. Centralized / SDN-Based

1- Probability-Based Path Discovery (PBPD 2020) [65] enables efficient path discovery and control message dissemination in dense nano-networks using a grid-based, probabilistic routing model governed by a centralized SDN controller. PBPD divides the network into a 3D virtual grid, with each cell hosting potential forwarders. The SDN controller monitors node distribution and link quality, computing a probabilistic model for each cell. It then generates routing tables that prioritize high-probability cells as next-hop candidates. These tables are periodically pushed to nano-routers, which follow the controller's instructions to forward packets, ensuring dynamic routing adaptability without burdening nodes with complex decisions. The protocol supports scalable and adaptive routing in dense environments, offloading complexity to the controller.

However, its effectiveness relies on continuous feedback and frequent updates, which can introduce control overhead and latency in dynamic or mobile scenarios.

3.2. Summary

The presented analysis in **Section 3** systematically categorizes the contemporary routing protocols for electromagnetic nano-networks based on their underlying techniques and mechanisms. The classification framework encapsulates a broad spectrum of techniques ranging from cognitive and reinforcement learning-based approaches, predictive algorithms using Kalman filters and fuzzy logic, swarm intelligence, temperature-aware routing, and probabilistic forwarding mechanisms. The accompanying Table 2 consolidates these techniques, highlighting the specific mechanisms employed by each protocol.

By structuring the table to group protocols with similar underlying techniques, it becomes evident that routing strategies in nano-networks are heavily influenced by the distinct constraints of nano-devices, such as limited energy reserves, computational capacity, and communication range. Notably, the synthesis reveals recurring trends in protocol design, including the reliance on centralized decision-making to optimize routing paths, the integration of predictive and learning-based algorithms to mitigate dynamic network conditions, and the deployment of energy-efficient data dissemination methods. These strategies aim to enhance packet delivery reliability, reduce latency, and maintain energy efficiency — core QoS metrics that will be further examined in Section 4.

4. QoS Metrics & Performance Evaluation in Nano-Network Routing

Quality-of-Service (QoS) evaluation serves as a fundamental benchmark for assessing the performance and effectiveness of routing protocols in electromagnetic nano-networks. Given the severe resource constraints and unique communication challenges at the nano-scale, four primary QoS metrics are pivotal: reliability, latency, throughput, and energy efficiency. While reliability ensures data integrity across the network, latency measures the end-to-end delay, throughput quantifies the effective data rate, and energy efficiency evaluates the consumed energy or network lifetime. Additional metrics, such as thermal regulation, congestion probability, buffer occupancy, scalability, and mobility support, are also considered, particularly in biomedical nano-networks. Section 3 classified contemporary routing protocols based on communication paradigms: data-centric, peer-to-peer, and data dissemination. In this section, we further align this classification with QoS metrics to address RQ2, focusing on how each protocol performs concerning these critical metrics. The analysis is systematically presented in Table 3, which provides a structured overview of the key protocols and their corresponding QoS performance under each communication paradigm.

4.1. Data-Centric Communication Protocols

Data-centric communication protocols primarily focus on data aggregation, query-driven dissemination, and event-based reporting to manage data flow from nano-nodes to a central gateway. The analysis of these protocols is presented in Table 3, which provides a comprehensive evaluation of each protocol's QoS performance based on reliability, latency, throughput, and energy efficiency.

Learning-based protocols such as E3A, 4-DMDP, and QL-MEC exhibit strong reliability and throughput due to their dynamic path selection and adaptive decision-making capabilities. However, these protocols typically incur higher latency due to the centralized learning and control operations. In contrast, optimization-based schemes like MILP, which leverage mathematical models for routing and bandwidth allocation, achieve superior throughput and energy efficiency but at the cost of increased computational complexity and latency.

Table 2. *Summary of the techniques employed by the contemporary routing protocols*

Technique/Mechanism	Protocols	Description
Reinforcement Learning (Q-Learning)	4-D-MDP, MDR-RL, QL-MEC	Adaptive routing based on Q-learning to optimize energy efficiency and data delivery under dynamic conditions.
Finite State Machine (FSM)	LCFSM	Deterministic routing through FSM, reducing memory usage and computational overhead.
Centralized Optimization (MILP)	MILP	Joint optimization of routing, bandwidth allocation, and sub-band assignment using a centralized MILP model.
Energy-Based Forwarding	EECORONA, EEPSN-Greedy	Nodes prioritize forwarding based on residual energy, minimizing redundant transmissions.
Cluster-Based Structure	DCCORONA, EEPSN-Greedy	Nodes are organized into clusters with designated Cluster Heads (CHs) for structured data forwarding.
Predictive Routing (Kalman Filter + Fuzzy Logic)	MRLSP	Link state prediction using Kalman filter and fuzzy logic to select optimal next-hop nodes.
Ring-Based Forwarder Selection	RFS, ERFS, 3D-RFS	Spatially-constrained forwarding based on concentric ring regions to reduce redundant transmissions.
Time-Based Ray Tracing	TBRT, ERT	Packet forwarding based on packet reception timing, reducing control overhead and redundant transmissions.
Probabilistic Forwarding	ERA-SDN, SR-ANS	Nodes probabilistically decide to forward based on sleep-wake cycles and observed network density.
Swarm Intelligence (Artificial Bee Colony)	ABC-OA	Node selection based on fitness evaluation using swarm intelligence to optimize energy use and data relevance.
Probabilistic Path Discovery	PBPD	SDN-based path discovery using probabilistic grid-based routing to optimize data dissemination.
Cognitive Routing and Adaptive Learning	E3A	Combines reasoning phase (adaptive routing based on current network state) and learning phase (long-term optimization based on historical data).
Temperature-Aware Routing	TAEE, SA, TA-IBN	Thermal management through data filtering (TAEE), simulated annealing optimization (SA), and temperature thresholding (TA-IBN).
Flow-Guided Opportunistic Routing	FGOR	Exploits flow dynamics (e.g., blood flow) to guide packet forwarding, integrating position and mobility gradients.
Dynamic Infrastructure (DIF) and Geo-Addressing	P2PAFS	Adaptive forwarder selection based on packet reception quality, integrating dynamic infrastructure and geo-addressing for multi-mode communication.

Thermal-aware protocols like TAEE, SA, and TA-IBN focus on thermal regulation, effectively managing energy efficiency and reliability by preventing overheated nodes from participating in routing. However, the use of temperature thresholds may lead to increased latency when nodes are temporarily excluded from communication. Predictive routing schemes like MRLSP maintain high reliability and energy efficiency through link state estimation and fuzzy logic-based forwarding, though they are computationally intensive and may face scalability challenges.

Cluster-based schemes, such as EEPSN-Greedy, and flow-guided routing strategies like FGOR, effectively balance QoS metrics by leveraging lightweight topology awareness, achieving accept trade-offs in energy, latency, and reliability.

The deterministic control approach in LCFSM ensures reliable, low-latency communication in static network settings with minimal computational demands. Lastly, ABC-OA employs swarm intelligence to optimize node selection and data smoothing, maintaining balanced QoS performance across metrics while incurring moderate complexity due to its two-phase search mechanism.The detailed QoS performance of these data-centric protocols is systematically presented in **Table 3**, which provides a structured comparison of each protocol's impact on reliability, latency, throughput, and energy efficiency.

4.2. Peer-to-Peer Communication Protocols

Peer-to-peer communication protocols are designed to facilitate direct node-to-node data exchange through multi-hop routing, emphasizing reliable data delivery and adaptive path selection in dynamic network environments. The QoS performance of these protocols is summarized in Table 3, which highlights the specific mechanisms employed to manage latency, energy fairness, and delivery reliability.Protocols such as EECORONA and DCCORONA effectively manage redundancy through counter-based and cluster-based mechanisms, ensuring robust performance across reliability, latency, and energy metrics. However, the overhead associated with cluster formation and rollback logic introduces moderate complexity.

Sleep-aware protocols like SR-ANS and ERA-SDN focus on energy conservation through sleep scheduling and probabilistic retransmissions, achieving significant energy savings at the potential cost of increased latency when destination nodes are asleep.

Ring-based forwarder selection schemes, including RFS, ERFS, and 3D-RFS, excel in energy efficiency and reliability in dense networks by spatially constraining forwarding zones, thereby reducing unnecessary retransmissions and mitigating collisions. Nonetheless, the complexity of 3D adaptations increases due to spherical shell management and power control mechanisms.

Ray-tracing protocols like ERT and Enhanced RT provide a coordinate-free, timing-based forwarding mechanism that significantly reduces latency and energy consumption. However, their reliance on femtosecond-scale synchronization poses practical challenges, increasing hardware complexity and implementation costs.MDR-RL effectively mitigates data loss through reinforcement learning and deflection routing, enhancing reliability in dynamic conditions. However, its reliance on Q-learning algorithms results in higher latency and computational cost.The comprehensive QoS evaluation of peer-to-peer communication protocols is presented in Figure 4, outlining the trade-offs between reliability, latency, throughput, and energy efficiency in each protocol.

4.3. Data-Dissemination Communication Protocols

Data dissemination protocols are designed to propagate data across network infrastructures, focusing on throughput, scalability, and controlled latency. These protocols employ both self-organizing infrastructures and centralized frameworks to coordinate data flow effectively.The P2PAFS protocol leverages a dynamic infrastructure model, adjusting forwarding probability based on packet reception quality and node density. This approach achieves balanced QoS performance but incurs moderate complexity due to adaptive infrastructure management.PBPD, on the other hand, employs a probabilistic grid-based routing model to optimize throughput and PDR in dense static networks. However, the protocol faces challenges related to latency and computational overhead when network dynamics fluctuate.The detailed QoS performance analysis of data dissemination protocols is systematically presented in Table 4, which highlights the impact of each protocol on reliability, latency, throughput, and energy efficiency.

4.4. Summary

The analysis of contemporary routing protocols reveals distinct strategies for addressing QoS metrics in electromagnetic nano-networks. Centralized control mechanisms (e.g., E3A, QL-MEC, MILP) consistently enhance reliability and throughput but introduce latency and computational overhead due to centralized processing. Decentralized approaches, including ring-based selection (RFS, ERFS), ray-tracing (ERT), and sleep-aware schemes (SR-ANS), prioritize energy efficiency and latency reduction, though they may sacrifice reliability in dynamic networks. Predictive mechanisms such as MRLSP and flow-guided strategies like FGOR effectively manage dynamic link states, sustaining balanced QoS performance but at the expense of computational complexity.The inclusion of Table 3 provides a structured overview of the QoS performance of each protocol under different communication paradigms, illustrating the diverse mechanisms employed to optimize key QoS metrics. This comprehensive evaluation not only addresses RQ2 but also sets the stage for **Section 5**, where we will further explore emerging techniques, hybrid frameworks, and adaptive architectures aimed at achieving comprehensive QoS optimization while minimizing computational overhead.

5. Challenges & Future Research Directions

Designing and implementing QoS-aware routing protocols for electromagnetic nano-networks presents substantial challenges given the extreme resource constraints, limited communication range, and dense node deployments typical of such networks. The objective of this section is to address RQ3: “*What are the key challenges in designing and implementing QoS-aware routing protocols for nano-networks?”* Through a comprehensive analysis of contemporary protocols, several critical challenges are identified, along with emerging research directions aimed at overcoming these limitations.

5.1. Challenges in QoS-Aware Routing for Nano-Networks

5.1.1. Energy Efficiency and Network Lifetime

Energy efficiency is a fundamental concern in nano-network routing, as the energy reserves of nano-nodes are severely limited and non-rechargeable. Protocols like EEPSN-Greedy**,** EECORONA, and QL-MEC have implemented various energy-aware routing strategies; however, the trade-off between minimizing energy consumption and maintaining reliable data delivery remains unresolved. While EEPSN-Greedy employs cluster-based, greedy selection to reduce active nodes, QL-MEC utilizes reinforcement learning to optimize routing paths based on network state information. Nevertheless, the computational overhead and data exchange required for learning-based protocols can significantly drain node energy.

Challenge: How to maintain optimal energy consumption without sacrificing data delivery reliability, especially in dense or highly dynamic topologies?

5.1.2. Scalability in Ultra-Dense Networks

As nano-networks are envisioned to support thousands of nodes in biomedical or environmental monitoring applications. This section synthesizes the key challenges identified across existing QoS-aware routing protocols and outlines future research directions aimed at optimizing nano-network performance. The insights derived from the analysis of contemporary protocols not only address RQ3 but also provide a foundation for the development of more robust, adaptive, and resource-efficient routing solutions tailored for the electromagnetic nano-network domain managing congestion and minimizing collision risks are critical. Protocols like ERFS and 3D-RFS attempt to mitigate redundant transmissions by implementing spatial ring-based forwarding and selective retransmission strategies. However, as node density increases, the computational and communication overhead associated with maintaining optimal forwarding sets also rises, potentially causing congestion and packet collisions.

Challenge: How to achieve scalable routing without increasing latency and overhead in ultra-dense networks?

5.1.3. Adaptive Routing in Dynamic and Mobile Networks

In biomedical applications, nano-nodes are subject to constant movement, particularly in flow-driven environments like blood vessels. Protocols such as 4-DMDP and FGOR leverage flow dynamics and mobility trends to predict optimal routing paths. However, maintaining reliable paths under unpredictable mobility remains challenging.

Challenge: How to implement adaptive routing that can predict and respond to network topology changes in real-time?

5.1.4. Computational Complexity and Hardware Constraints

Nano-nodes possess extremely limited computational power and memory capacity, restricting the implementation of complex routing algorithms. Protocols such as MILP**,** QL-MEC, and MDR-RL employ computationally intensive optimization and learning algorithms to optimize routing and bandwidth allocation. However, such methods can quickly overwhelm resource-constrained nano-nodes.

Challenge: How to balance computational complexity and QoS optimization given hardware limitations?

5.1.5. Thermal Regulation in Biomedical Nano-Networks

The terahertz (THz) band, while offering considerable bandwidth, is highly susceptible to molecular absorption, resulting in thermal buildup that can damage surrounding tissues in biomedical contexts. Protocols like TAEE**,** SA, and TA-IBN focus on mitigating thermal effects while maintaining data throughput. However, striking a balance between thermal regulation and reliable data transmission remains challenging.

Challenge: How to prevent thermal buildup without compromising data throughput and latency?

Table 3. *Summary of QoS performance of peer-to-peer communication protocols*

Protocol	Reliability (PDR)	Latency	Throughput	Energy Efficiency	Additional QoS Metrics	Computational Complexity
EECORONA	Reduces packet loss through adaptive redundancy control.	Counter-based control minimizes delay by reducing retransmissions.	Optimizes data flow by limiting redundant retransmissions.	Reduces retransmissions, conserving node energy.	Scalability through adaptive redundancy control.	Moderate – counter-based redundancy control and adaptive forwarding.
DCCORONA	Rollback mechanism ensures data delivery despite link failures.	Cluster-based forwarding reduces hop count and minimizes delay.	Cluster-based structure reduces unnecessary transmissions, increasing throughput.	Cluster-based forwarding minimizes active transmitters, conserving energy.	Scalability and fault tolerance through rollback and fallback mechanisms.	Moderate – cluster management and rollback mechanism increase processing.
SR-ANS	Probabilistic retransmission reduces packet loss in sleeping nodes.	Sleep scheduling may introduce delay for nodes entering sleep mode.	Adaptive sleep scheduling prevents collisions, maintaining steady data flow.	Sleep scheduling reduces node energy consumption.	Congestion control through adaptive sleep scheduling.	Low – simple sleep scheduling and probabilistic forwarding.
ERA-SDN	Selective retransmission minimizes packet loss due to sleeping nodes.	Backoff timers may introduce retransmission delays.	Efficient retransmission reduces congestion, maintaining data flow.	Selective retransmission conserves energy by limiting active nodes.	Data freshness through priority-based retransmission selection.	Low – selective retransmission based on wake probability.
MDR-RL	Deflection routing ensures data delivery even under buffer overflow.	Reinforcement learning may introduce delays during training phase.	Adaptive routing mitigates packet loss, enhancing throughput.	Adaptive routing prevents excessive energy use by balancing node load.	Buffer management and congestion control through deflection routing.	High – reinforcement learning and dual-table deflection routing.
3D-RFS	Spatially constrained forwarding minimizes packet loss in dense networks.	Controlled forwarding reduces unnecessary hops, minimizing delay.	Dynamic region adjustment balances throughput and node density.	Controlled forwarding reduces redundant transmissions, conserving energy.	Link stability through spatially constrained forwarding.	Moderate – spatial region adjustment and controlled forwarding.
MRLSP	Timing-based forwarding confirms forwarding eligibility, reducing packet loss.	Timing-based forwarding reduces propagation delay.	Selective forwarding mitigates redundant transmissions, optimizing data flow.	Timing-based forwarding reduces unnecessary forwarding, saving energy.	Data accuracy through timing synchronization and handshake mechanisms.	High – timing synchronization and handshake protocol increase complexity.
RFS	Selective forwarder designation reduces redundant transmissions, enhancing packet delivery.	Spatial ring selection reduces forwarding nodes, minimizing delay.	Reduces redundant transmissions, maintaining steady data flow.	Reduces active forwarders, conserving node energy.	Scalability through controlled forwarding and limited retransmissions.	Moderate – spatial ring identification requires power level differentiation.
ERFS	Intersection-based forwarding minimizes redundant nodes, ensuring data delivery reliability.	Intersection-based selection reduces unnecessary hops, lowering latency.	Intersection-based forwarding minimizes collisions, optimizing throughput.	Intersection-based control reduces active transmitters, conserving energy.	Link stability through intersection-based selection and controlled forwarding.	Moderate – intersection determination increases processing overhead.
Enhanced Ray Tracing	Handshake mechanisms confirm forwarding eligibility, reducing packet loss due to double propagation.	Timing-based forwarding reduces propagation delay but requires precise synchronization.	Selective forwarding reduces unnecessary retransmissions, optimizing data flow.	Reduces redundant transmissions through timing-based control, saving energy.	Data accuracy through precise timing synchronization and handshake protocol.	High – timing synchronization and handshake protocol increase computational load.

Protocol	Reliability (PDR)	Latency	Throughput	Energy Efficiency	Additional QoS Metrics	Computational Complexity
P2PAFS	Dynamic forwarder selection based on reception quality reduces packet loss.	Counter-based flooding reduces redundant retransmissions, lowering delay.	Optimizes data flow through adaptive forwarder selection, maintaining steady throughput.	Adaptive forwarder selection conserves node energy by limiting active transmitters.	Data dissemination with multi-mode support for data-centric and peer-to-peer communication.	Moderate – counter-based flooding and reception quality assessment increase processing overhead.
PBPD	Probabilistic path discovery enhances data delivery reliability in dense networks.	Centralized path computation may introduce slight delays in large networks.	Efficient path selection maximizes bandwidth utilization, enhancing data flow.	Probabilistic routing reduces redundant transmissions, conserving node energy.	Scalability and congestion control through probabilistic path selection.	High – centralized path computation and probabilistic forwarding increase computational load.

5.1.6. Interference and Channel Utilization in THz Band

The THz band offers substantial communication bandwidth but is susceptible to molecular absorption and multipath fading. Protocols like MILP and ERT address interference through sub-band allocation and timing-based forwarding mechanisms. However, coordinating channel access in ultra-dense nano-networks remains a significant challenge.

Challenge: How to maximize throughput while minimizing interference in the THz band?

5.1.7. Security and Data Integrity

Security remains an underexplored area in nano-network routing, especially in biomedical applications where data integrity is crucial. Protocols focused on PDR, such as ERA-SDN and SR-ANS, aim to ensure reliable data delivery but do not incorporate data integrity verification mechanisms.

Challenge: How to secure data transmission in nano-networks without incurring excessive energy or computational overhead?

5.2. Emerging Research Directions

The comprehensive analysis of routing protocols for electromagnetic nano-networks reveals several critical research gaps that, if addressed, can significantly advance the development of QoS-aware routing. The following research directions offer potential pathways to overcome current limitations while aligning with the unique characteristics of nano-communication systems.

Cross-Layer Optimization in Nano-Networks is a pressing necessity, as most existing protocols focus narrowly on network-layer metrics such as hop count and residual energy, overlooking key dependencies with MAC and physical layers. The terahertz (THz) band, in particular, introduces challenges like molecular absorption and high path loss that cannot be resolved through network-layer strategies alone. To address this, future routing protocols should adopt cross-layer frameworks that holistically optimize routing paths, transmission power, and MAC scheduling. These frameworks must also account for temperature control to prevent thermal buildup, especially in biomedical applications. Predictive models leveraging real-time channel state information (CSI) can further enhance routing decisions by enabling dynamic sub-band allocation and interference mitigation.

Machine Learning-Driven Adaptive Routing offers another promising direction, particularly reinforcement learning techniques that can dynamically respond to evolving network topologies and conditions. However, the high computational and communication overhead of centralized learning must be overcome. Decentralized learning approaches such as federated learning and edge-based reinforcement learning could be used to distribute training across nano-nodes, thus minimizing overhead. Moreover, transfer learning can allow nodes to adapt faster by leveraging prior experiences, and predictive models based on mobility or flow patterns can improve path selection accuracy in dynamic environments like the bloodstream.

Hybrid Communication Frameworks should be explored to unify the three dominant paradigms data-centric, peer-to-peer, and data dissemination into a cohesive system capable of adapting communication modes based on contextual factors. Many current protocols are tailored for a single communication paradigm, limiting flexibility in heterogeneous environments. Future frameworks should enable nodes to autonomously switch between modes depending on data criticality, node density, or energy availability. Opportunistic multi-hop routing combined with dynamic relay selection could improve scalability and ensure efficient use of resources in congested or resource-constrained scenarios.

Multi-Objective Optimization (MOO) in QoS-Aware Routing is essential to meet the multifaceted requirements of nano-networks, where performance often depends on balancing trade-offs between energy consumption, reliability, latency, and throughput. Most protocols currently focus on optimizing a single metric, limiting their effectiveness in real-world deployments. Future routing schemes should adopt decentralized MOO frameworks using heuristic techniques such as genetic algorithms or fuzzy logic to dynamically evaluate network states. These approaches can enable adaptive routing decisions that satisfy multiple QoS requirements simultaneously while remaining lightweight enough to operate within hardware limitations.

Interference and Channel Utilization in the THz Band is another vital research area, particularly given the growing density and mobility of nano-nodes. Existing solutions using static sub-band allocation or simple timing-based forwarding cannot fully cope with dynamic interference patterns. To overcome this, multi-channel frameworks that adaptively allocate sub-bands based on real-time interference sensing should be developed. Cognitive radio and spectrum sensing technologies could be integrated to dynamically monitor channel conditions and avoid collisions. Additionally, mobility-aware interference mitigation mechanisms that adjust power levels based on node movement and flow direction could further enhance data delivery reliability.

Secure and Reliable Data Transmission remains underdeveloped despite its importance in privacy-sensitive applications like biomedical monitoring. Most current protocols lack integrated mechanisms for ensuring data integrity and security against potential threats. Future work should focus on embedding lightweight encryption and authentication into routing decisions to secure transmissions without imposing significant overhead. Secure routing frameworks that can detect and isolate malicious or malfunctioning nodes are also needed, alongside cross-layer security protocols that exploit signal characteristics—such as timing or frequency patterns—for implicit authentication.

5.3. Summary

This section synthesizes the challenges and emerging research directions in QoS-aware routing for nano-networks. It not only addresses RQ3 but also establishes a foundation for future work aimed at developing more robust, scalable, and adaptive routing solutions. By focusing on cross-layer optimization, predictive routing, and dynamic clustering, future protocols can more effectively balance QoS metrics, including energy efficiency, latency, and throughput, while maintaining network stability and data integrity.

6. Conclusion

This study represents the first systematic literature review (SLR) dedicated to electromagnetic nano-networks, uniquely offering a comprehensive examination of the intersection between Quality of Service (QoS) and routing protocols in this emerging field. By categorizing routing protocols into Data-Centric, Peer-to-Peer, and Data Dissemination communication modes, this work introduces a novel classification framework that not only structures existing routing strategies but also aligns them with specific application domains and their associated QoS expectations. This classification framework serves as a conceptual foundation for understanding how distinct communication modes address the inherent challenges of nano-networking, thereby providing a coherent basis for future protocol development.

Addressing the first research question (RQ1), the review systematically identified contemporary routing protocols and examined their classification based on communication paradigms. The findings reveal a prevailing focus on energy efficiency, driven by the severe resource constraints of nano-nodes. However, emerging applications in biomedical monitoring, environmental sensing, and industrial nanonetworks necessitate a more comprehensive QoS approach that concurrently addresses latency, throughput, and data reliability alongside energy conservation. The proposed classification framework not only organizes the existing protocols but also underscores the strategic role of communication modes in shaping the expected QoS. This highlights the need for adaptive routing mechanisms that can effectively balance diverse QoS requirements across varying application scenarios.

The second research question (RQ2) explored the key QoS metrics used to assess routing protocol performance in nano-networks. The analysis reveals a predominant emphasis on energy conservation, with relatively less attention given to latency and throughput optimization, while security remains an underexplored domain. This gap underscores the necessity for multi-objective optimization frameworks capable of reconciling conflicting QoS metrics, particularly in heterogeneous and dynamic nano-network environments characterized by node mobility and varying data-criticality.

The third research question (RQ3) focused on identifying the core challenges in designing and implementing QoS-aware routing protocols for nano-networks. The analysis identified several critical challenges, including computational complexity, scalability, thermal regulation, interference management, node mobility, and security. Adaptive routing approaches that leverage learning-based or predictive mechanisms demonstrate potential for addressing network dynamics and optimizing resource allocation; however, their computational overhead can overwhelm resource-constrained nano-nodes. Similarly, while some protocols incorporate thermal regulation strategies to mitigate temperature buildup in biomedical settings, integrating these mechanisms with other QoS-oriented frameworks remains an open challenge. Moreover, the growing focus on THz communication introduces substantial interference management challenges, necessitating advanced channel access and coordination mechanisms that can effectively mitigate signal degradation and minimize packet loss.

The findings of this study underscore the importance of cross-layer optimization, predictive routing, and context-aware communication strategies to bridge the gap between current protocol designs and the diverse QoS requirements of emerging nano-network applications. By establishing a framework that connects communication paradigms with expected QoS outcomes, this review not only addresses the immediate research gaps but also lays the groundwork for future protocol designs that can adaptively respond to evolving application demands in electromagnetic nano-networks.

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