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Protocoles De Routage Et Qualité De Service Dans Les Nano-Réseaux Électromagnétiques

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Abstract:

Electromagnetic nano-networks present unprecedented opportunities for biomedical monitoring, Software-Defined Metamaterials (SDMs), and quantum computing systems. However, they are constrained by limited power, short communication ranges, and dense node deployments. To address these challenges, this thesis conducts a systematic literature review (SLR) that classifies existing routing protocols based on data-centric, peer-to-peer, and data dissemination paradigms, identifying key research gaps and proposing three novel routing schemes that significantly enhance QoS while optimizing energy consumption and data delivery reliability. EECORONA introduces a set of energy-efficient flood-based protocols that reduce redundant transmissions and extend network lifetime through selective forwarding and probabilistic retransmission control. DCCORONA leverages a cluster-based multi-hop framework that improves data delivery reliability and mitigates network congestion in dense deployments through adaptive clustering and energy-aware routing. P2PAFS is the first framework to support peer-to-peer, upward, and downward communication modes, enabling flexible and dynamic routing in heterogeneous networks. Comprehensive evaluations demonstrate that the proposed schemes achieve notable improvements in Packet Delivery Ratio (PDR), latency, throughput, and energy efficiency, positioning them as benchmark solutions for next-generation QoS-aware nano-networks.

Titre : Protocoles de Routage et Qualité de Service dans les Nano-réseaux Électromagnétiques

Mots-clés : Nano-réseaux, IoNT, Bande Terahertz, Qualité de Service, Protocoles de Routage

Résumé :

Les nano-réseaux électromagnétiques offrent des opportunités sans précédent pour la surveillance biomédicale, les métamatériaux définis par logiciel (SDM) et les systèmes d'informatique quantique. Cependant, ils sont contraints par une puissance limitée, des portées de communication courtes et des déploiements de nœuds denses. Pour relever ces défis, cette thèse propose une revue systématique de la littérature (SLR) qui classe les protocoles de routage existants en fonction des paradigmes centrés sur les données, de pair à pair et de diffusion des données, identifiant des lacunes de recherche clés et proposant trois nouveaux schémas de routage qui améliorent considérablement la qualité de service (QoS) tout en optimisant la consommation d'énergie et la fiabilité de la livraison des données. EECORONA introduit un ensemble de protocoles de diffusion énergétiquement efficaces qui réduisent les transmissions redondantes et prolongent la durée de vie du réseau grâce au transfert sélectif et au contrôle de retransmission probabiliste. DCCORONA exploite un protocole multi-hop basé sur des clusters qui améliore la fiabilité de la livraison des données et atténue la congestion du réseau dans les déploiements denses grâce à une mise en cluster adaptive et un routage conscient de l'énergie. P2PAFS est le premier protocole à prendre en charge les modes de communication pair à pair, montants et descendants, permettant un routage flexible et dynamique dans des réseaux hétérogènes. Des simulations extensives démontrent que les schémas proposés obtiennent des améliorations notables en termes de ratio de livraison de paquets (PDR), de latence, de débit et d'efficacité énergétique, les positionnant comme des solutions de référence pour les nano-réseaux de nouvelle génération sensibles à la qualité de service (QoS).

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اللَّهُمَّ لَا سَهْلَ إِلَّا مَا
جَعَلْتَهُ سَهْلًا، وَأَنْتَ
تَجْعَلُ الحَزْنَ إِذَا شِئْتَ
سَهْلًا

Associated Papers

Several chapters in this thesis appeared in several papers in the form of conference and journal articles

Conference:

The following conference paper is derived from **Chapter 4**

[1] Bouchedjera, Islam Amine, Zibouda Aliouat, and Lemia Louail. "**Eecorona: Energy efficiency coordinate and routing system for nanonetworks.**" International Symposium on Modelling and Implementation of Complex Systems. Cham: Springer International Publishing, 2020.

The following conference paper is derived from **Chapter 5**

[2] Bouchedjera, Islam Amine, et al. "**Dccorona: Distributed cluster-based coordinate and routing system for nanonetworks.**" 2020 11th IEEE Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON). IEEE, 2020.

Journal:

The following journal manuscript is derived from **Chapter 6**

[3] Bouchedjera, Islam Amine, Lemia Louail, and Zibouda Aliouat. "**Addressing and flood-based communications for the software-defined metamaterial paradigm.**" Nano Communication Networks 28 (2021): 100336.

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Chapter 1
Context and Motivation

1.1 Introduction

The emergence of nanotechnology, initially conceptualized by Richard Feynman in his seminal 1959 lecture, “There’s Plenty of Room at the Bottom,” has evolved into a transformative scientific domain, enabling the development of nanoscale devices equipped with sensing, processing, and communication capabilities **[81]**. These devices form the building blocks of nanoscale communication networks, where the interaction among nodes occurs at molecular and atomic levels, introducing unprecedented opportunities in fields such as biomedicine, industrial automation, environmental monitoring, and quantum computing systems **[2][3].**

A critical enabler of nanoscale communication is the Terahertz (THz) frequency band (0.1-10 THz), facilitated by the unique properties of graphene-based antennas. Graphene’s exceptional conductivity and tunability allow nanodevices to operate at THz frequencies, delivering ultra-high data rates and extensive bandwidth. However, while the THz band offers promising data transmission capabilities, it is also characterized by severe path loss, molecular absorption, and scattering, which significantly limit communication range to mere millimeters **[14]**. This limitation complicates the design of effective routing protocols, especially when attempting to maintain Quality of Service (QoS) parameters such as reliability, latency, throughput, and energy efficiency.

In conventional wireless networks, achieving QoS often involves centralized control structures and extensive routing tables. However, in nano-networks, such approaches are infeasible due to the extreme resource constraints of nanodevices, including minimal power reserves, limited processing capacity, and basic memory resources. Consequently, the development of QoS-aware routing protocols must incorporate strategies that ensure data reliability and minimize latency while optimizing energy consumption and thermal regulation [47][53]**.** Moreover, the envisioned applications, such as biomedical sensing, Software-Defined Metamaterials (SDMs) [21], in-package wireless systems [107], and quantum computing networks [103], demand ultra-dense node deployments, often involving thousands or millions of nanonodes operating within confined areas. This density not only exacerbates network congestion and packet collisions but also heightens thermal buildup, particularly in biomedical networks where prolonged THz transmissions can lead to tissue damage and cellular disruption. Consequently, the challenge of maintaining QoS in such scenarios necessitates the development of adaptive, energy-efficient, and thermal-aware routing protocols capable of mitigating thermal effects and optimizing data delivery in ultra-dense deployments. In biomedical applications, where nanonodes are deployed within fluidic or vascular environments, maintaining QoS becomes even more complex due to the mobility of nodes and fluctuating link quality. Existing protocols primarily target static networks, with limited mechanisms to handle node mobility. In such contexts, achieving QoS requires the integration of mobility-aware routing mechanisms that can dynamically adjust forwarding paths based on node movement patterns and link stability**.** Scalability is another critical aspect of QoS in nano-networks, particularly in SDMs and in-package wireless systems, where data traffic from densely deployed nodes can quickly lead to network congestion and data redundancy. Uncontrolled data dissemination can exacerbate packet collisions and increase energy consumption, thereby compromising QoS. Addressing these issues requires the integration of scalability-centric routing strategies, such as probabilistic forwarding, congestion control mechanisms, and dynamic infrastructure frameworks that can regulate node participation and manage data propagation intensity.

Lastly, conventional routing protocols often operate independently across the physical, MAC, and network layer**s**, resulting in suboptimal routing decisions that fail to account for link quality variations, node energy levels, and network congestion. The integration of cross-layer optimization frameworks can significantly enhance QoS by coordinating link selection, power allocation, and retransmission control across multiple layers, effectively reducing latency and mitigating packet collisions in multi-hop networks. These challenges collectively highlight the need for the development of multi-objective, QoS-aware routing protocols that can effectively balance energy efficiency, scalability, communication reliability, and thermal regulation in dense, dynamic, and resource-constrained electromagnetic nano-networks.

1.2 Problem Statement and Research Objectives

Despite the promising potential of electromagnetic nano-networks, the deployment of QoS-aware routing protocols remains prsents significant challenges that are not adequately addressed by conventional wireless routing protocols. Unlike traditional networks, nano-networks operate under severe resource constraints, including limited energy reserves, minimal processing capacity, and basic memory resources. Furthermore, the use of THz frequencies, while providing extensive bandwidth, also introduces intense path loss and thermal buildup, particularly in dense network deployments. Existing routing protocols, primarily designed for conventional wireless networks, are ill-suited to address the unique operational conditions of nano-networks, especially in scenarios involving high node density, dynamic node mobility, and stringent thermal regulation requirements. Additionally, the absence of effective scalability mechanisms, mobility support, and cross-layer optimization in current protocols further exacerbates data delivery issues, leading to packet loss, network congestion, and rapid energy depletion.

Addressing these challenges necessitates the development **of** energy-efficient, scalable, and adaptive routing protocols that can maintain Quality of Service (QoS) while considering the specific operational characteristics of nano-networks. Therefore, the central research question guiding this study is: **“***How can energy-efficient, scalable, and adaptive routing protocols be designed and implemented to ensure Quality of Service (QoS) in electromagnetic nano-networks while addressing the specific operational challenges of dense node deployments, mobility support, and thermal regulation?***”.**

1.3 Thesis Contributions

This thesis presents a comprehensive investigation into the design and implementation of QoS-aware routing protocols for electromagnetic nano-networks, focusing on addressing the challenges of energy efficiency, scalability, mobility support, and thermal regulation. The contributions of this thesis are structured around four key components, each targeting a specific aspect of nano-network communication to ensure reliable data delivery and optimal resource management in dense, heterogeneous network deployments.

1.3.1 EECORONA: Energy-Efficient Routing for 2D Nanonetworks

The first major contribution of this thesis is the proposition of EECORONA, a suite of three flood-based routing schemes designed to enhance the energy efficiency of point-to-point communication in dense 2D nanonetworks. To the best of our knowledge, this work represents the first study in the nanonetwork field that proposes and evaluates a point-to-point routing scheme considering the severe power limitations of nanodevices. The proposed schemes enhance the capabilities of the CORONA protocol, a widely recognized benchmark protocol, by integrating energy-aware mechanisms and selective flooding control to optimize data dissemination and develop the following three versions:

- **Energy-based Probabilistic CORONA Routing:** This version leverages residual energy metrics to dynamically adjust the probability of forwarding packets, effectively **reducing redundant transmissions** while maintaining data delivery reliability.
- **Counter-based CORONA Routing:** This variant incorporates a counter-based mechanism that restricts the number of retransmissions per node, minimizing packet collisions and network congestion in ultra-dense deployments.
- **Hybrid CORONA Routing:** Integrating both probabilistic and counter-based mechanisms, this version provides a balanced approach, optimizing energy consumption without compromising communication reliability.

EECORONA is particularly relevant for applications in SDMs and in-package wireless systems, where dense node deployments and limited power reserves necessitate energy-efficient data dissemination strategies. Simulation results demonstrate the effectiveness of EECORONA in achieving significant energy savings while maintaining acceptable packet delivery ratios and latency levels compared to conventional routing schemes.

1.3.2 DCCORONA: Cluster-Based Multi-Hop Routing

The second contribution addresses the need for adaptive multi-hop routing in dynamic and dense network environments through the development of DCCORONA, a cluster-based routing protocol designed to enhance data delivery reliability in ultra-dense 2D nanonetworks. To the best of our knowledge, the present work introduces the first distributed cluster-based multi-hop point-to-point routing scheme specifically tailored for 2D dense homogeneous nanonetworks. DCCORONA introduces a distributed clustering mechanism, enabling nodes to self-organize into clusters and elect cluster heads based on residual energy levels and node centrality. The protocol is structured into three key components:

- **Self-Addressing and Cluster Formation:** Nodes assign local identifiers based on their geographical coordinates, facilitating the formation of clusters without centralized control, thereby reducing communication overhead and enhancing scalability.
- **Cluster Head Election and Data Forwarding:** Cluster heads are dynamically selected based on energy reserves and connectivity, ensuring a balanced distribution of communication tasks and effectively extending network lifetime.
- **Multi-Hop Routing and Maintenance:** Data is relayed through the selected cluster heads, minimizing the number of forwarding nodes and reducing packet collisions and network congestion, thereby maintaining data delivery reliability under high-density conditions.

DCCORONA is particularly applicable to biomedical applications, where dense nanonode deployments require efficient data aggregation and multi-hop communication to maintain QoS while minimizing energy consumption.

1.3.3 P2PAFS: Framework for Three Modes of Communication (Peer-to-Peer, Upward, Downward)

The third contribution focuses on the development of P2PAFS, a comprehensive routing framework that addresses the unique communication requirements of Software-Defined Metamaterials (SDMs) and in-package wireless systems by supporting three distinct communication modes: peer-to-peer, upward, and downward**.** To the best of our knowledge, P2PAFS is the first and only framework that simultaneously supports these three communication modes, enabling seamless data exchange and directive broadcasting across the network**.**

- **Peer-to-Peer Mode:** Enables direct data exchange between node pairs, facilitating localized communication and collaborative data processing**.**
- **Upward Communication Mode:** Supports the transmission of data from nanonodes to an external controller, **ensuring** effective data aggregation and external monitoring**.**
- **Downward Communication Mode:** Facilitates directive broadcasting from the external controller to specific nodes or clusters, enabling network reconfiguration and command dissemination**.**

P2PAFS employs a self-addressing system and a dynamic infrastructure (DIF) mechanism, allowing nodes to classify themselves as forwarders or regular nodes based on residual energy and communication priority. This approach not only optimizes energy consumption but also reduces network congestion and thermal buildup, making P2PAFS particularly relevant for advanced SDMs, in-package wireless systems, and quantum computing networks**..**

1.3.4 QoS-Aware Routing Protocols in Electromagnetic Nano-Networks: A Systematic Literature Review

In addition to the development of novel routing protocols, this thesis presents a systematic literature review (SLR) that comprehensively analyzes the current state-of-the-art in QoS-aware routing protocols for electromagnetic nano-networks. The SLR is structured around three primary communication paradigms**:** data-centric, peer-to-peer, and data dissemination, providing a detailed examination of existing protocols within each category.

- **Data-Centric Communication:** Analyzes schemes that focus on data aggregation, query dissemination, and event-driven reporting, emphasizing their applicability to applications such as environmental monitoring and biomedical sensing.
- **Peer-to-Peer Communication:** Evaluates routing protocols designed **for** direct node-to-node communication, identifying strategies for minimizing energy consumption and reducing latency in densely deployed networks.
- **Data Dissemination Communication:** Investigates schemes that employ controlled flooding, probabilistic forwarding, and adaptive retransmission, highlighting their relevance to SDMs and in-package wireless networks.

The SLR not only categorizes existing protocols but also identifies key research gaps and emerging trends**,** such as the need for cross-layer optimization, AI/ML-driven routing strategies, and thermal-aware communication frameworks. These findings provide a comprehensive context for the subsequent chapters, informing the design and evaluation of the proposed routing protocols.

Together, these contributions provide **a** holistic framework for QoS-aware routing in electromagnetic nano-networks, addressing critical challenges in energy efficiency, scalability, mobility support, and thermal regulation. By integrating energy-aware mechanisms, adaptive routing strategies, and cross-layer optimization frameworks, this thesis seeks to advance the state-of-the-art in nano-network communication, setting the stage for the deployment of next-generation routing protocols in diverse application domains, including biomedical sensing, SDMs, and quantum communication systems.

1.4 Thesis Organization

This thesis is structured into two main parts, organized as follows:

Part One: State of the art

This part provides a comprehensive review of the fundamental concepts and existing works in the domain of electromagnetic nano-networks, focusing on network architecture, communication paradigms, and QoS metrics. It includes the following chapter:

- **Chapter 2: Background and Literature Review** — This chapter provides a comprehensive overview of electromagnetic nano-networks, covering key components such as nano-device architecture, graphene-based antennas, and THz band communication techniques. It also explores various application domains, including smart materials, biomedical systems, military operations, in-package wireless networks, quantum computing, environmental monitoring, and agriculture, emphasizing the diverse capabilities of nano-networks. Additionally, the chapter examines the communication paradigms in nano-networks, categorizing protocols as data-centric, peer-to-peer, or data dissemination-based, and elucidates their role as key enablers of the aforementioned application.

Part Two: Contributions

This part presents the original research contributions of the thesis. It includes the following chapters:

- **Chapter 3: Systematic Analysis of Routing Protocols** — This chapter presents a systematic analysis and classification of existing routing protocols, aligning them with the communication paradigms identified in Chapter 2 (data-centric, peer-to-peer, and data dissemination). The objective is to identify design trends, assess protocol effectiveness based on QoS metrics, and highlight key research gaps that inform the proposed contributions.

- **Chapter 4: EECORONA — Energy-Efficient Routing for 2D Nanonetworks** — This chapter introduces EECORONA, a suite of three flood-based routing schemes designed to enhance energy efficiency in dense 2D nanonetworks. The proposed schemes extend the CORONA protocol by integrating selective forwarding and probabilistic retransmission mechanisms to reduce redundant transmissions while maintaining data delivery reliability.

- **Chapter 5: DCCORONA — Cluster-Based Multi-Hop Routing** — This chapter presents DCCORONA, a distributed cluster-based multi-hop routing protocol tailored for dense, homogeneous 2D nanonetworks. It introduces a novel clustering mechanism that enables nodes to self-organize based on geographic coordinates and elect cluster heads based on residual energy, optimizing multi-hop data transmission.

- **Chapter 6: P2PAFS — Framework for Three Modes of Communication** — This chapter details P2PAFS, a framework specifically designed to address the three communication modes: peer-to-peer, upward, and downward, applicable to Software-Defined Metamaterials (SDMs) and in-package wireless systems. The framework integrates adaptive infrastructure mechanisms to regulate node participation and data dissemination intensity, effectively balancing energy consumption and communication reliability.

- **Chapter 7: QoS Analysis, Challenges, and Future Directions** — This chapter provides a comprehensive evaluation of the proposed routing protocols based on core QoS metrics: PDR, latency, throughput, and energy efficiency. Additionally, it synthesizes key challenges identified in nano-network routing, such as scalability, mobility support, thermal regulation, and cross-layer optimization, and outlines potential **future research directions**, including AI/ML-driven adaptive frameworks and cross-layer decision-making strategies.
- **Chapter 8: Conclusion and Synthesis** — This chapter consolidates the findings, summarizing the main contributions and practical implications of the proposed protocols while providing recommendations for future research in QoS-aware routing for electromagnetic nano-networks.

I

STATE OF THE ART

Chapter 2
Background and Literature Review

This chapter reviews the background of IoNT by examining the following aspects: the development of graphene-based nano-technologies, THz channels, potential applications, anticipated QoS metrics satisfaction, and routing protocols for electromagnetic nanonetworks.

2.1 IoNT: Overview

Thanks to the development of graphene-based nano technologies, the sensing resolution of WSNs is now miniaturized by nanosensors to a molecular level. Taking advantage of the properties of nano materials, nanosensors with nano-meter scales could sense nanoscale events; however, the individual nanosensor shows extremely limited capacity due to its tiny size **[35][54][115]**. Therefore, they are expected to form nanonetworks for complex sensing tasks.

Nanonetworks will enable the interaction with remote nano-machines by means of broadcasting and multihop communication mechanisms. Classical communication paradigms need to be revised for the nano-scale. Communication in the nano-scale can be realized through nano-mechanical, acoustic, electromagnetic and chemical or molecular communication means **[5][81]**. For the time being, it is still not clear how these nano-machine devices will communicate. However, we present the two motivating paradigm:

- **Molecular communication:** It refers to the transmission and reception of information encoded in molecules **[5]**. Due to their compact size and specific operational domain, molecular transceivers can be seamlessly integrated into nano-devices. These transceivers are capable of detecting specific molecules and releasing others either in response to internal commands or after performing certain processing tasks. The released molecules propagate in one of three ways: via spontaneous diffusion in a fluidic medium (diffusion-based), through guided flow in a fluidic medium (flow-based) **[7]**, or by being actively transported through predefined pathways by carriers (walkway-based). This fundamentally distinct communication paradigm requires the development of new channel models **[81]**, network architectures **[48]**, and communication protocols. However, the practical application of this paradigm faces several challenges: first, the data rate is limited due to the slow propagation speed of molecules in media like liquid and air; second, the communication link is highly sensitive to environmental factors, such as temperature; and third, releasing molecules in vivo poses a risk of interfering with organ functionality **[61].**

- **Graphene-based electromagnetic communication:** It refers to the transmission and reception of electromagnetic radiation using components developed from advanced nano-materials, specifically graphene-based nanoantennas. Recent breakthroughs in molecular and carbon electronics have paved the way for a new generation of nano-scale electronic components, including nano-batteries, nano-memories, nano-scale logic circuits, and nano-antennas [115]. From a communication standpoint, the distinct properties of these novel nano-materials determine specific operational bandwidths for electromagnetic radiation [4], the response time of emissions, and the power output for a given input energy. These advancements represent a significant shift in the existing analytical channel models [30], network architectures, and communication protocols [48].

Consequently, we focus on graphene-based electromagnetic nano-communication, which draws considerable attention from a broad scientific community. It is also suitable for various propagation mediums (e.g., in-body, free space, on-chip) and has the potential to meet the applications' requirements (more details in Sections 2.3 and 2.4). In the rest of this section, the context of graphene-enabled electromagnetic nano-communication in the THz frequencies is discussed in four aspects: the characteristics of graphene, peculiarities of THz communications, network architecture, and potential applications.

2.1.1 Graphene-based Nano Technology

Since its discovery, graphene has emerged as a groundbreaking material in nanotechnology due to its exceptional mechanical, electrical, and thermal properties. It is regarded as the strongest material ever measured, exhibiting extraordinary tensile strength and resilience under extreme stress, making it ideal for high-impact applications [81]. Despite its atomic-scale thickness, graphene maintains exceptional fracture toughness, retaining structural integrity even under substantial impact forces. Additionally, its superior electron mobility across a wide temperature range facilitates rapid electron transport and efficient data transmission — crucial attributes for nanoscale communication systems. Another notable feature of graphene is its exceptional thermal conductivity, enabling effective heat dissipation and preventing thermal buildup, which is critical for nano-devices operating in densely populated and confined environments. These unique characteristics collectively position graphene as a fundamental enabling material for the development of advanced nanoscale devices, including sensors, transceivers, energy storage units, and biomedical implants [115].

Among the various applications, graphene-based integrated nanosensors — consisting of sensors, antennas, transistors, and capacitors — are anticipated to be one of the most promising outcomes. Currently, Graphene NanoRibbons (GNRs) and Carbon NanoTubes (CNTs) are being developed to fabricate components of integrated nanosensors, such as THz signal modulators, THz plasmonic antennas, sensing units, and transceivers [2-6]. However, despite the significant advancements, there remains a gap between the current state of graphene-based nanotechnology and its large-scale deployment, especially when compared to the more mature macro-scale manufacturing and modeling techniques. To bridge this gap, graphene is expected to be integrated with conventional materials like SiGe and GaN in a hybrid approach, enhancing its practical applicability in nanoscale systems **[115]**.

2.1.2 THz Channel

Due to the extremely small antenna size of nano-devices, the THz band has emerged as a promising communication frequency for electromagnetic nano-networks. This section examines the distinctive characteristics, challenges, and modulation techniques associated with the THz band in the context of nano-communication systems.

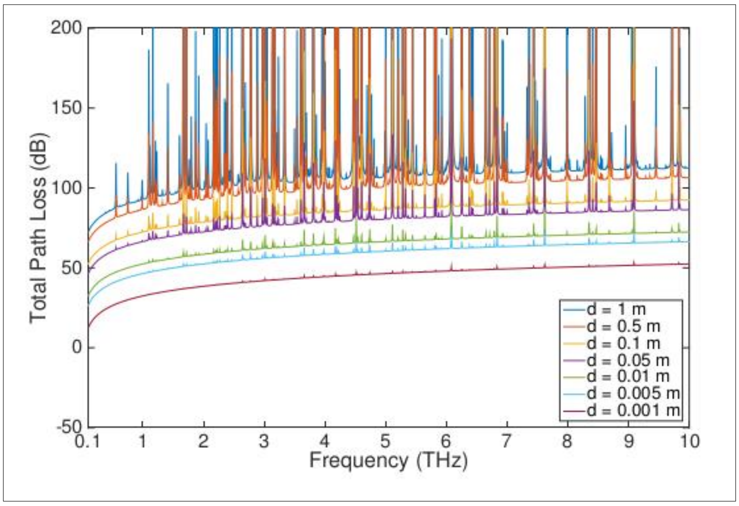


Fig. 2.1: The path loss in the THz band

2.1.2.1 Peculiarities of the THz Band

The THz band (0.1 THz – 10 THz) is considered the next frontier in wireless communications due to its capacity to provide extremely high data rates, reaching the Tbps level **[54]**. In comparison to adjacent frequency bands, the THz band offers unique advantages and specific limitations. Below the THz range, the channel capacity is constrained by limited bandwidth. Conversely, frequencies above the THz range face challenges related to regulated energy levels and severe path loss, both of which significantly reduce the achievable data rates.

Currently, the THz band has gained considerable research attention due to its potential to support a wide range of applications across different scales **[103][107][113][114]:**

- **Macroscale Applications:** The vast bandwidth available in the THz band can enable high-speed, short-range directional wireless links, making it ideal for small cells, access networks, and backhaul networks in 5G systems, as well as wireless local/personal area networks and military communication networks **[42][58]**.
- **Nanoscale Applications:** At the nanoscale, the compact size of nano-antennas naturally aligns with the operational frequency range of the THz band. Potential applications in this context

include in-vivo health monitoring, chemical detection systems, and wireless on-chip communication [107].

2.1.2.2 Networking Challenges of the THz Band

Despite its extensive bandwidth, the THz band presents several challenges that hinder its effective utilization:

- **Physical Layer Challenges:** Generating, detecting, and synchronizing THz signals requires advanced hardware design and manufacturing techniques [116]. Additionally, molecular absorption caused by molecular resonance leads to frequency-selective path loss and increased noise temperature (illustrated in Fig. 2.1) [2]. This effect is particularly pronounced for certain molecules, such as water, significantly reducing the available bandwidth for long-distance transmission. Furthermore, the inherently high frequency of THz signals limits the transmission range. Addressing these limitations is critical to fully harness the potential of the THz band.

- **Link Layer Challenges:** At the link layer, medium access control (MAC) solutions and error coding schemes must be tailored to the unique characteristics of THz links. Unlike conventional wireless networks, interference and collision are less significant due to the short transmission time enabled by high data rates [12][50]. Thus, MAC protocols must be adapted to efficiently manage ultra-fast, high-frequency links.

- **Network Layer Challenges:** At the network layer, two primary challenges arise:
  - **Channel Utilization and Routing:** The end-to-end channel capacity is highly sensitive to environmental factors like humidity, which can significantly impact the path capacity. Thus, routing and forwarding mechanisms must account for distance-related bandwidth variations.
  - **Node Addressing:** Given the small-scale yet high-speed nature of THz networks, appropriate node addressing schemes are essential to maintain efficient communication [50][81].

2.1.2.3 THz Pulse Modulation

To address the limited energy capacity and small antenna size of nano-devices, a modulation scheme known as Time Spread On-Off Keying (TS-OOK) has been proposed [8]. As illustrated in Fig. 2.2, TS-OOK employs ultrashort femtosecond pulses to encode information. Data transmission is achieved by interleaving these pulses with predetermined time intervals Ts. In this scheme, a ‘1’ bit is represented by a power pulse of duration Tp, while a ‘0’ bit is indicated by a period of silence. The key parameters of TS-OOK include the pulse duration Tp and the inter-symbol interval Ts, with the spreading ratio $\beta = Ts/Tp$ serving as a crucial metric.

A distinctive feature of TS-OOK is its use of temporal spacing between individual bits, as depicted in Fig. 2.2. Given the constraints of nano-device hardware, emitting consecutive pulses without adequate gaps is infeasible. Consequently, each bit in TS-OOK is separated by a time interval Ts, which is substantially longer than the pulse duration. This approach ensures reliable data transmission while minimizing energy consumption and mitigating potential hardware limitations.

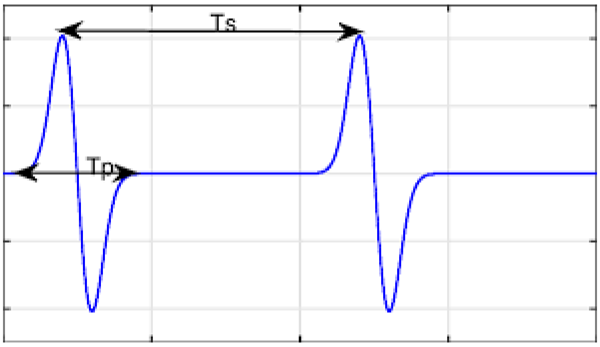


Fig. 2.2: The path loss in the THz band

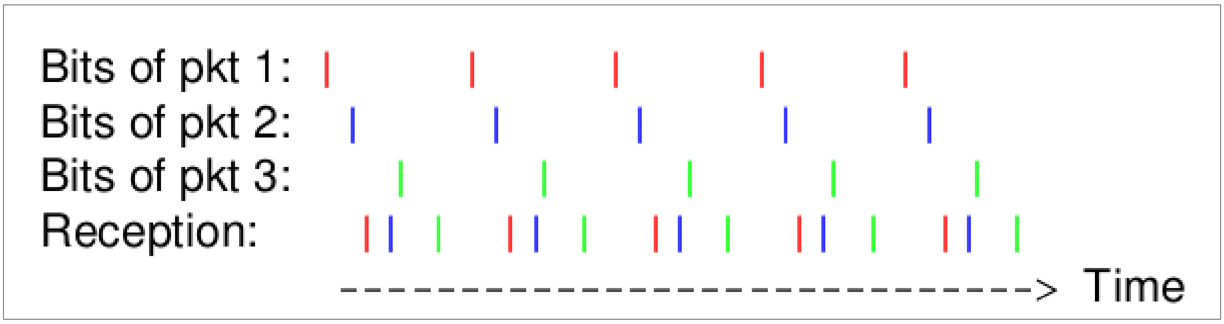


Fig. 2.3: Packet overlapping by bit interleaving in TS-OOK.

The proposed duration Tp for a single pulse in TS-OOK is 100 femtoseconds. Given the need for a significant gap between consecutive bits due to hardware limitations, the spreading ratio (β=Ts /Tp) often reaches high values, such as 1000. This ratio plays a critical role in the effective bandwidth of the channel (1/T p = 10 Tb/s).

Another notable feature of **TS-OOK** is its potential for packet overlapping, as illustrated in Fig. 2.3. This occurs when bits from multiple packets are interleaved across a shared transmission channel, resembling time-division multiple access (TDMA) but operating at the frame level **[12]**. While this approach can significantly enhance channel capacity, it can also introduce inefficiencies in frame retransmission during multi-hop forwarding scenarios if not adequately managed. Moreover, hardware limitations are a critical consideration, as they restrict the number of frames a node can process simultaneously, potentially leading to packet loss and a reduction in effective channel capacity.

Collisions in TS-OOK present a distinct challenge. Unlike conventional communication schemes, collisions occur when a '0' bit (silence) is being received, and a '1' bit arrives concurrently, effectively overshadowing the '0'. Interestingly, not all collisions in TS-OOK are detrimental. For instance, simultaneous collisions involving two '0' bits are non-destructive since both represent silent intervals. Furthermore, the impact of collisions is spatially dependent, affecting only those receivers positioned at specific distances from the source and receiving bits simultaneously. Thus, understanding and mitigating collision effects is crucial for optimizing TS-OOK performance in nanoscale networks.

2.1.3 Nano-device and Network Architecture

This section introduces key concepts related to the Internet of Nano-Things (IoNT), encompassing nano-machines, their development approaches and components, nano-networks and their architecture, and the overall IoNT framework.

2.1.3.1 Nano-machine

Nanotechnology facilitates the miniaturization and fabrication of devices at scales ranging from 1 to 100 nanometers [1][3]. At this scale, a **nano-machine** is considered the most fundamental functional unit. It is defined as a nano-scale device capable of executing specific tasks such as communication, computation, data storage, sensing, and actuation. Due to their minimal complexity and size, nano-machines perform simple operations restricted to their immediate environment.

There are three primary approaches for the development of nano-machines, as illustrated in Fig. 2.4 [16][32][35][54]:

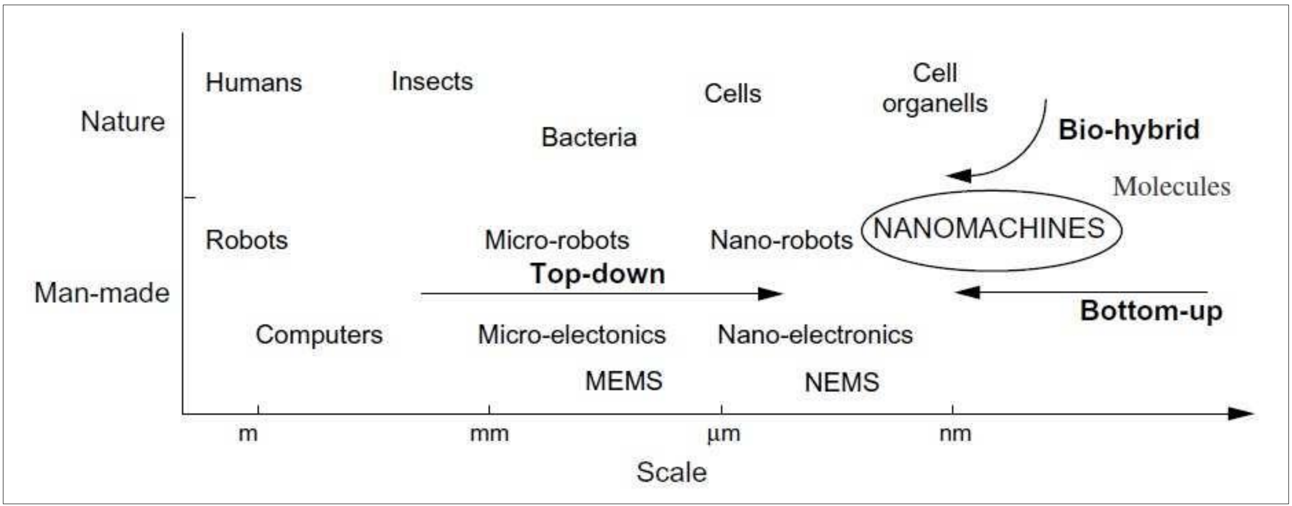


Fig. 2.4: Approaches for the development of nano-machines

- **Top-down approach:** In this approach, nano-machines are developed by scaling down existing microelectronic and micro-electro-mechanical technologies without achieving atomic-level precision. Advanced manufacturing techniques such as electron beam lithography and micro-contact printing are employed to fabricate nano-scale components that retain the architecture of their micro-scale counterparts, such as microelectromechanical systems (MEMS). Nano-electromechanical systems (NEMS) components are examples of devices developed through this approach [20]. However, this method is still in its early stages, with only basic mechanical structures like nano-gears successfully fabricated. The 14 nm lithographic process has enabled the integration of nano-scale electronic components into single devices, but large-scale, complex nano-machine assembly remains a challenge.

- **Bottom-up approach:** This approach involves constructing nano-machines from molecular components that self-assemble based on molecular recognition principles, arranging molecule by molecule. While manufacturing techniques capable of precisely assembling molecules do not yet exist, theoretical designs such as molecular differential gears and pumps have been proposed using discrete molecular components. Once feasible, this process — known as molecular manufacturing — could enable the efficient production of nano-machines through precise molecular arrangement. Current advancements in this approach focus on self-assembling molecular devices such as molecular switches and shuttles.
- **Bio-hybrid approach:** The bio-hybrid approach leverages naturally occurring biological structures in living organisms, particularly within cells, as functional nano-machines. Examples include nano-biosensors, nano-actuators, molecular storage units, and control systems, all of which are integral to cellular processes such as cell division. This approach proposes utilizing biological nano-machines as models for developing artificial nano-machines or incorporating them as building blocks in more complex nano-systems, such as nano-robots. For instance, bacteria have been explored as controlled propulsion mechanisms for transporting micro-scale objects.

Each approach leverages different fabrication techniques and materials, contributing to the diversity in nano-machine design and functionality.

2.1.3.2 Nano-machine architecture

A nano-machine can consist of one or more components, resulting in varying levels of complexity, ranging from simple molecular switches to sophisticated nano-robots **[16][30].** The most comprehensive nano-machines are expected to incorporate the following architectural components:

- **Control Unit:** The control unit is responsible for executing instructions to carry out specific tasks. It manages and coordinates all other components within the nano-machine. Additionally, it may include a storage unit to retain essential operational data and control algorithms.
- **Communication Unit:** This unit comprises a transceiver capable of transmitting and receiving data at the nano-scale, often using molecules as the communication medium.
- **Reproduction Unit:** The reproduction unit is designed to fabricate and assemble each component of the nano-machine using external elements, effectively replicating the nano-machine. It is equipped with instructions for executing these tasks autonomously.
- **Power Unit:** The power unit supplies energy to all components of the nano-machine. It can harvest energy from external sources such as light, temperature gradients, or chemical reactions and store it for subsequent use.

- **Sensors and Actuators:** These components function as interfaces between the nano-machine and its surrounding environment. A variety of sensors (e.g., temperature sensors, chemical sensors) and actuators (e.g., clamps, pumps, motors) can be integrated to enable interaction with external stimuli.

Currently, such complex nano-machines have yet to be realized. However, nature provides examples of similar systems, particularly in the form of living cells, which possess analogous functional architectures. According to the bio-hybrid approach, these biological structures can serve as models to understand the principles governing nano-machine operation and interaction. This knowledge can be leveraged to develop bio-inspired nano-machines for specific applications. In **Fig. 2.5**, we present a component mapping between a generic nano-machine architecture and a living cell, highlighting the parallels between biological nano-machines and their synthetic counterparts.

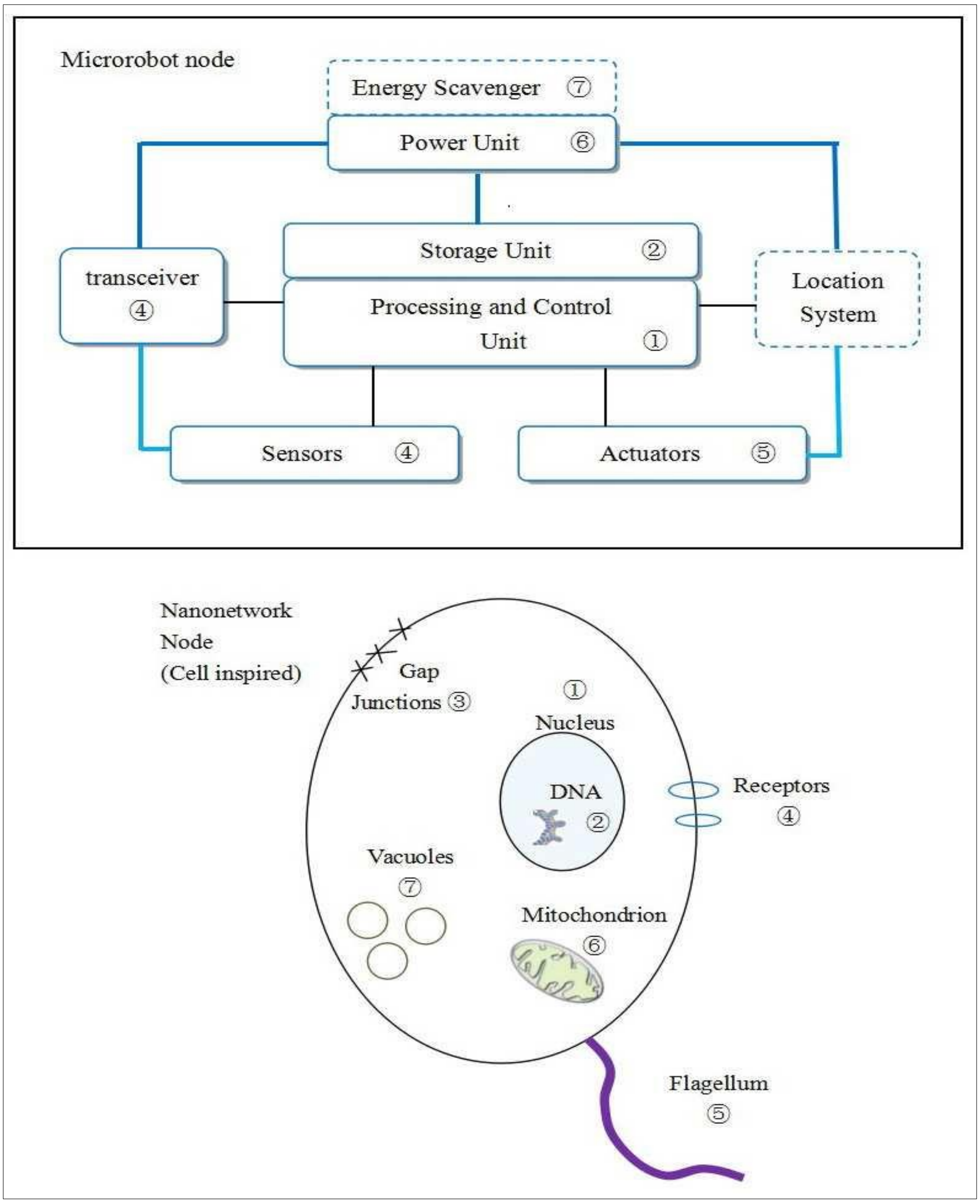


Fig. 2.5: Functional architecture mapping between nano-machines of a micro or nano-robot, and nano-machines found in cells.

2.1.3.3 Nano-network

A **nano-network** or nano-scale network refers to a group of interconnected nano-machines, typically ranging in size from a few hundred nanometers to a few micrometers [2]. These nano-machines, although individually limited to simple tasks such as computing, data storage, sensing, and actuation, can collectively perform more complex operations by coordinating, sharing, and fusing information.

Nano-networks significantly enhance the capabilities of individual nano-machines by extending their operational range and enabling cooperative functionalities. This networking capability opens up new avenues for nanotechnology applications in various domains. By integrating multiple nano-machines into a cohesive network, nano-networks facilitate the execution of more advanced tasks and increase the overall system's functional complexity and spatial coverage.

2.1.3.4 Internet of Nano-Things

The **Internet of Nano-Things (IoNT)** refers to the integration of nanoscale devices with conventional communication networks and ultimately the Internet, establishing a new networking paradigm [32][69]. While the IoNT shares several similarities with the Internet of Things (IoT), its distinctive feature is that the interconnected devices are miniaturized to nanoscale dimensions, typically ranging from 0.1 to 100 nanometers. Despite their size, these devices hold the potential to revolutionize various application domains through pervasive sensing, monitoring, and control capabilities. The architecture of the IoNT can be categorized into the following components:

- **Nano-nodes:** are the simplest and smallest nano-machines, capable of performing basic computational tasks, storing minimal data, and communicating over extremely short distances. Due to their limited energy resources and communication capabilities, nano-nodes are typically used for specific applications such as biological nano-sensors inside the human body or nanoscale communication devices integrated into everyday objects like books, keys, or paper folders.
- **Nano-routers:** possess relatively higher computational resources compared to nano-nodes, allowing them to aggregate data from multiple nano-machines. They can also manage nano-node operations by exchanging simple control commands (e.g., on/off, sleep, read value). However, this increase in processing capability results in larger device sizes, making their deployment more invasive.
- **Nano-micro interface devices:** these devices act as bridges between the nanoscale and microscale, aggregating data from nano-routers and relaying it to conventional microscale networks. Nano-micro interfaces are hybrid devices that can communicate using both nano-communication techniques and classical communication protocols, enabling seamless integration of nanoscale networks with larger systems.
- **Gateway:** provide remote access and control over the entire IoNT system by connecting nanoscale networks to the broader Internet. For instance, in an intrabody network scenario, a smartphone can act as a gateway by receiving health-related data from a nano-micro interface on the wrist and transmitting it to a healthcare provider. In industrial or office environments, conventional modem-routers can serve as gateways for nano-device networks.

By integrating these components, the IoNT architecture supports the deployment of nanoscale networks for various applications, ranging from biomedical monitoring and environmental sensing to industrial automation and smart infrastructure.

Recent market research indicates that the global **IoNT market** is projected to reach **USD 46.09 billion by 2028**, with a compound annual growth rate (CAGR) of **22.1%** during the forecast period **[102]**. The key factors driving this revenue growth include increased government funding for nanotechnology advancements, the rising prevalence of severe diseases, and escalating private sector investments in the development and deployment of nanoscale technologies.

2.2 Nanonetworks Application Fields

The development of nanomachines and nanonetworks is still in its conceptual phase, necessitating substantial efforts to achieve effective implementation of this emerging paradigm. Despite these challenges, it is possible to envision future applications capable of providing reliable solutions to complex problems that current technologies cannot adequately address. Nanonetworks composed of organic or inorganic nanomachines derived from nanotechnology hold significant promise for diverse application domains that require nano-scale information acquisition and decision-making capabilities. At present, the potential applications of nanonetworks can be categorized into several key areas, one of which is:

2.2.1 Programmable matter applications

Programmable matter refers to materials capable of altering their physical properties, such as shape, density, modulus, conductivity, and optical characteristics, in a programmable manner based on user input or autonomous sensing **[21]**. This concept envisions materials inherently capable of processing information, enabling a new generation of intelligent material systems with integrated sensing, actuation, and computation functionalities. The primary applications of programmable matter include:

- **Adaptive Aerodynamic Profiles:** Programmable materials that can modify surface properties to optimize aerodynamic performance in real-time.
- **Military Equipment with Camouflage Capability:** Materials that can dynamically adjust color or texture to blend into different environments for enhanced stealth.
- **Self-Reconfiguring Modular Robotics:** Systems composed of modular robotic units capable of autonomously altering their structure to perform different tasks or repair damaged components by replacing failed modules.
- **Self-Repairing Structures:** Materials that can detect and self-repair damage by modifying or replacing defective components, potentially extending the operational lifespan of devices.

At the nanoscale, programmable matter is exemplified by **Claytronics**, a field focused on developing reconfigurable nanoscale robots known as **claytronic atoms (catoms)**. These sub-millimeter computing units are envisioned to move, communicate, change color, and electrostatically connect with other catoms to form various shapes and structures. By assembling into larger mechanisms, claytronic systems could significantly expand the functional capabilities of nanoscale devices, enabling transformative applications in fields ranging from robotics to biomedical engineering.

2.2.2 Bio-medical applications

The biomedical field is considered one of the most promising domains for the application of nanonetworks, as nanomachines can be engineered with specific capabilities such as molecular-level control, biocompatibility, and bio-stability, enabling them to interact effectively with human organs and tissues. Potential biomedical applications include **[45][57][70][111]:**

- **Immune System Enhancement:** Nanomachines can be designed to assist in detecting and eliminating harmful agents such as viruses, microbes, and cancer cells. By enhancing the body's natural immune response, these nanomachines can make treatments for critical diseases less taxing and more tolerable for patients.
- **Bio-Hybrid Implants:** Nanonetworks can support the development of bio-hybrid implants intended to replace or support failing biological components, such as damaged organs, nerve pathways, or tissues. In particular, bio-hybrid implants are envisioned to revolutionize neurosurgery by restoring central nervous system tracks and providing seamless interfaces between implants and the surrounding biological environment.
- **Drug Delivery Systems:** Nanoscale drug delivery systems can be developed to compensate for deficiencies in natural metabolic processes by administering essential substances or stimuli regularly. Examples include the automatic administration of insulin for diabetes patients or the targeted delivery of neurotransmitters for treating neurodegenerative diseases.
- **Health Monitoring:** Embedded nanosensor networks can continuously monitor various metabolic parameters, such as glycoside levels, cholesterol, uric acid, red blood cell count, and lymphocyte levels. This real-time data can be used for early diagnosis of diseases, enabling healthcare providers to initiate timely and more effective treatments.
- **Genetic Engineering:** Nanonetworks can facilitate advancements in genetic engineering by deploying nanomachines capable of manipulating molecular and genetic structures, thereby enhancing or repairing genetic material at the nanoscale.

2.2.3 Industrial and consumer goods applications

Nanonetworks have significant potential in industrial and consumer sectors, particularly in the development of new materials, manufacturing processes, and quality control systems. Potential applications include [70][86][89][90]:

- **Programmable Matter:** Nanonetworks can enable programmable matter composed of micro-robots capable of reorganizing themselves to form various shapes. Wireless communication among these micro-robots enhances the efficiency and responsiveness of reorganization algorithms, making them adaptable for diverse industrial applications.
- **Food and Water Quality Control:** Nanosensor networks can be deployed to monitor the quality of food and water reserves. By detecting toxic chemical or biological agents, these networks can provide real-time monitoring and contamination alerts, thus ensuring food and water safety.
- **Functionalized Materials and Objects:** Nanonetworks can be integrated into advanced fabrics and materials to provide new functionalities such as antimicrobial and stain-resistant surfaces. For instance, during a pandemic, nano-functionalized protective products could significantly reduce contamination and mortality rates by limiting viral transmission among citizens and healthcare workers. This would mitigate socio-economic impacts and contain the spread of infectious diseases to localized outbreaks.

2.2.4 Military applications

In military settings, the deployment of nanonetworks varies based on the application. While battlefield surveillance and maneuvering require dense deployment over large areas, applications focused on monitoring soldier performance are more localized. Key military applications include [42][89][90]:

- **Defense Against Weapons of Mass Destruction:** Nanonetworks can be deployed across battlefields to detect chemical, biological, or radiological agents and coordinate defensive responses. This rapid detection capability enhances situational awareness and mitigates the impact of mass destruction weapons.
- **Nano-Functionalized Equipment:** Advanced military gear can be manufactured using nano-functionalized materials embedded with nanonetworks. These materials could provide functionalities such as adaptive camouflage, temperature regulation, and real-time location tracking of injured or deceased soldiers, thereby improving battlefield efficiency and safety.

2.2.5 Environmental applications

Nanotechnology, inspired by natural biological systems, presents several promising environmental applications that conventional technologies cannot achieve. Key applications include **[11][91]**:

- **Animals and Biodiversity Control:** Nanonetworks can be deployed in natural habitats to monitor and control animal species using pheromone-based communication. By triggering specific interactions, these systems can facilitate the monitoring and study of animal populations, contributing to biodiversity management and conservation efforts.
- **Air Pollution Control:** Nanonetworks can be utilized in urban areas to monitor air quality and detect harmful pollutants in real time. In megacities prone to severe air pollution, nanosensor networks can provide continuous monitoring, enabling timely alerts and intervention measures. Additionally, nano-filters designed to capture and neutralize pollutants can purify contaminated air, mitigating the health impacts associated with air pollution.

2.2.6 Agriculture Applications

With the global population rapidly increasing, the demand for agricultural products is escalating. However, arable land expansion is reaching its limits, necessitating more efficient agricultural practices. Nanonetworks and nanotechnology offer several promising solutions **[11][91]**:

- **Genetic Engineering:** Nanomachines can be employed to develop high-yield and disease-resistant plant species through targeted genetic modifications. This approach can enhance crop productivity and mitigate the effects of adverse environmental conditions.
- **Disease Detection and Pathogen Control:** Nanosensor networks can facilitate early detection of crop diseases, enabling timely interventions to prevent pathogen spread. Once pathogens are identified, nanoactuators can be activated to deliver targeted treatments, eradicating disease agents effectively.
- **Soil and Crop Monitoring:** Nanosensors can detect nanoparticles and contaminants in the soil that may inhibit crop growth. These systems can also monitor soil moisture, nutrient levels, and environmental conditions, optimizing irrigation and fertilization practices to maximize crop yield and reduce resource wastage.

2.2.7 Quantum Computing Systems

Quantum computing represents a revolutionary paradigm in data processing, leveraging the principles of quantum mechanics to perform complex computations that are infeasible for classical systems. In this domain, nanonetworks are envisioned to play a critical role in facilitating data exchange between quantum processors and classical computing units, addressing the inherent challenges of maintaining data integrity, reducing latency, and optimizing thermal management in densely packed quantum circuits [103][107]. Quantum processors require ultra-fast, low-latency communication links to transmit qubits, the fundamental units of quantum information, across processing units and memory arrays. Nanonetworks equipped with graphene-based transceivers operating in the THz band can enable rapid qubit exchange with minimal power consumption, ensuring high data transfer rates over extremely short distances. This capability is crucial for implementing quantum error correction codes, which necessitate real-time data synchronization to maintain the coherence of quantum states. Beyond individual processors, quantum communication networks are envisioned to interconnect quantum nodes to form localized quantum clusters, where nanoscale transceivers facilitate inter-node communication. Such networks must be capable of maintaining qubit fidelity and preventing data loss, particularly in environments susceptible to electromagnetic interference. Quantum key distribution (QKD) protocols, leveraging the inherent properties of qubits, can provide secure communication links, preventing eavesdropping and data breaches **[107]**.

2.2.7 Wireless Networks In-Package (WiNiP)

With the increasing demand for high-performance computing and data processing, conventional wired interconnects in multi-core processors have become a significant bottleneck **[107]**. Wireless Networks In-Package (WiNiP) offer a promising solution by employing THz wireless communication links to interconnect multiple cores and memory units within a single chip package. WiNiP systems leverage graphene-based THz antennas and transceivers to enable ultra-fast data transfer between processor cores and memory units, minimizing latency and reducing physical interconnect overhead. Unlike wired interconnects, THz wireless links provide greater flexibility and scalability, facilitating communication across densely packed cores without extensive wiring or signal interference **[103]**.

2.3 QoS Metrics and Performance Analysis

In electromagnetic nano-networks, achieving and maintaining Quality of Service (QoS) is pivotal to ensuring reliable data communication under stringent resource constraints. Unlike conventional wireless networks, nano-networks operate in highly dense and dynamic environments with extremely limited power reserves, minimal processing capabilities, and severe path loss at THz frequencies **[47]**. As a result, defining appropriate QoS metrics and optimizing routing protocols to effectively balance these parameters becomes crucial. The following key QoS metrics are particularly relevant in the context of nano-networks and play a vital role in the diverse application domains discussed previously:

2.3.1 Reliability:Ensuring Data Integrity and Transmission Success

Reliability measures the accuracy and completeness of data delivery across the network, quantified as the Packet Delivery Ratio (PDR) — the ratio of successfully delivered packets to the total number of transmitted packets. In nano-networks, reliability is a critical metric given the high path loss at THz frequencies and dense node deployments**,** which can lead to data collisions and packet loss.

- **Biomedical Applications:** In medical monitoring systems, maintaining data integrity is paramount, especially in intrabody nanonetworks where data loss could result in misdiagnosis or incorrect treatment. For instance, nanosensors tracking cancer biomarkers must deliver critical health data to external receivers with minimal packet loss.
- **Quantum Computing Systems:** In quantum networks, ensuring data integrity is essential for quantum error correction protocols, where even minor data loss can disrupt qubit synchronization, compromising the accuracy of quantum computations.
- **Environmental Monitoring:** Reliability is equally significant in environmental monitoring applications, where nanosensors collect and transmit data on pollutant concentrations, chemical leaks, or air quality**,** necessitating robust data delivery mechanisms to ensure timely and accurate reporting of hazardous conditions**.**

2.3.2 Latency: Minimizing Data Transmission Delays

Latency, defined as the end-to-end delay in data transmission, is a vital QoS metric in applications requiring real-time data delivery. In nano-networks, latency can be exacerbated by multi-hop communication, network congestion, and limited processing capabilities, particularly in densely populated networks.

- **Smart and Programmable Materials:** In SDMs, where nanonodes collaborate to dynamically alter electromagnetic properties, latency must be minimized to maintain real-time reconfiguration of metamaterial surfaces.
- **Quantum Computing Systems:** Quantum networks demand ultra-low latency to synchronize quantum states and prevent qubit decoherence, necessitating adaptive routing schemes that prioritize low-latency data paths.
- **Wireless Networks In-Package (WiNiP):** In multi-core processor packages, maintaining low latency is crucial for **high-speed inter-core communication**, ensuring that data is relayed rapidly to avoid processing delays and bottlenecks.

2.3.3 Throughput: Maximizing Data Transmission Efficiency

Throughput quantifies the effective data rate achieved across the network, typically measured in bits per second (bps). Achieving high throughput is challenging in nano-networks due to severe path loss, frequent collisions, and constrained power resources.

- **Industrial Monitoring:** In industrial IoNT systems, throughput is critical for real-time process monitoring, where sensors continuously transmit operational data to centralized control units. Optimizing throughput ensures that large volumes of sensor data are delivered without congestion or data loss.
- **Quantum Computing Systems:** High throughput is also essential in quantum systems, where large volumes of quantum data must be exchanged rapidly between quantum processors and classical computing nodes. However, achieving high throughput without compromising data integrity is a significant challenge due to limited communication range and high path loss in THz communication.
- **Agriculture Applications:** In precision agriculture, throughput is vital for aggregating sensor data on soil moisture, nutrient levels, and crop health, enabling comprehensive field analysis and decision-making.

2.3.4 Energy Efficiency: Optimizing Power Consumption

Energy efficiency is a critical design consideration in nano-networks, where nodes typically operate on energy harvesting mechanisms or limited power reserves. The objective is to maximize network lifetime by minimizing unnecessary retransmissions, collisions, and idle listening.

- **Biomedical Applications:** In intrabody communication systems, maintaining energy efficiency is crucial to prevent rapid node depletion, which could compromise data transmission of vital health parameters. Energy-aware routing protocols that implement probabilistic forwarding and selective retransmission can significantly extend network lifetime while maintaining data reliability.
- **Wireless Networks In-Package (WiNiP):** WiNiP systems demand strict energy efficiency to prevent thermal hotspots in densely packed chips, requiring routing protocols to regulate transmission power and adjust data dissemination intensity based on thermal conditions.
- **Environmental Monitoring:** In large-scale environmental sensor networks, energy-efficient data dissemination is necessary to preserve node functionality and prevent network partitioning, especially in remote or inaccessible areas where node recharging is not feasible.

2.3.5 Scalability: Maintaining Performance in Ultra-Dense Networks

Scalability assesses a protocol's ability to maintain network performance as the number of nodes increases, particularly relevant in ultra-dense deployments such as SDMs, biomedical implants, and WiNiP systems.

- **SDMs:** In smart materials, nanosensors may be deployed in thousands or millions of nodes, requiring protocols capable of regulating node participation and mitigating broadcast storms to prevent data collisions and reduce network congestion.
- **Quantum Computing Systems:** Quantum networks demand scalable communication frameworks **capable of** synchronizing multiple quantum processors and managing high data traffic volumes, especially as quantum systems scale to incorporate more qubits and processors.
- **Precision Agriculture:** In agriculture, scalability is critical for aggregating sensor data across extensive farmlands, requiring routing protocols that can adaptively manage data dissemination intensity based on node density and sensor locations.

2.3.6 Thermal Regulation: Mitigating Heat Buildup in Dense Networks

Thermal regulation is a critical QoS metric in biomedical and in-package wireless networks, where prolonged THz transmissions can induce thermal buildup, potentially causing tissue damage or hardware malfunctions.

- **Biomedical Applications:** In intrabody networks, thermal regulation is vital to prevent overheating during prolonged data transmission**, particularly in** sensitive tissues such as blood vessels and organs. Thermal-aware protocols can dynamically adjust transmission power and schedule data transmissions to mitigate heat generation.
- **WiNiP Systems:** In densely packed chips, thermal regulation is essential to prevent heat accumulation between processor cores, necessitating protocols that monitor temperature levels and dynamically adjust transmission intensity based on thermal feedback.

2.3.7. Mobility Support: Adapting to Node Movement and Dynamic Topologies

Mobility support is particularly relevant in applications involving dynamic environments, such as biomedical systems and environmental monitoring, where nodes may move within fluidic or aerial environments.

- **Biomedical Applications:** In blood vessels or tissues, nanosensors are constantly in motion, necessitating mobility-aware routing mechanisms **that can** adjust forwarding paths based on node movement patterns and link stability.

- **Environmental Monitoring:** In aerial sensor networks, wind currents or other environmental factors may displace nodes, requiring routing protocols capable **of** tracking node positions and dynamically reconfiguring data paths to maintain communication reliability.

Overall, the diverse application domains of nanonetworks impose distinct QoS requirements, ranging from energy efficiency and thermal regulation in biomedical systems **to** low-latency communication and data integrity in quantum networks. Satisfying these QoS metrics is not only a critical enabler of the proposed application scenarios but also a fundamental requirement for the effective deployment of nanonetworks in real-world environments. Thus, the integration of adaptive, multi-objective routing protocols that effectively balance these QoS parameters across varying network conditions is imperative for the next generation of nano-network architectures.

2.4 Conclusion

This chapter has provided a comprehensive overview of the foundational concepts and emerging trends in electromagnetic nano-networks, emphasizing the pivotal role of graphene-based nanotechnology in enabling nanoscale communication within the Terahertz (THz) band. The unique electrical, thermal, and mechanical properties of graphene-based devices have been highlighted as critical enablers for the realization of efficient nanoscale communication systems.

Additionally, we examined a wide range of application domains where nano-networks are expected to play a transformative role, including biomedical monitoring, Software-Defined Metamaterials (SDMs), environmental monitoring, industrial and consumer goods, and quantum computing systems. Each of these application domains presents distinct operational requirements, ranging from ultra-low latency data exchange in quantum computing to thermal regulation in biomedical systems, underscoring the need for adaptive routing strategies that can balance Quality of Service (QoS) parameters effectively.

The chapter also discussed the key QoS metrics essential for evaluating routing protocols in nano-networks, including reliability, latency, throughput, energy efficiency, scalability, and thermal regulation. Ensuring optimal performance across these QoS metrics is vital for the successful deployment of nano-networks, particularly in resource-constrained and densely populated environments where node power limitations and communication range are significant constraints.

In conclusion, the insights gained in this chapter provide a foundational understanding of the architectural and operational aspects of nano-networks, setting the stage for the subsequent part of the thesis. The following chapters will systematically address the identified challenges by proposing three novel routing frameworks — EECORONA, DCCORONA, and P2PAFS — each designed to optimize QoS metrics under specific network conditions, ranging from dense peer-to-peer networks to multi-hop cluster-based frameworks and hybrid communication system

Chapter 3
Systematic Analysis of Routing Protocols

3.1 Introduction and Motivation

Routing in electromagnetic nano-networks presents significant challenges due to extreme resource constraints, limited communication range, and dense node deployment. Unlike conventional communication networks, nano-networks operate with highly restricted energy resources, minimal computational power, and severe communication limitations imposed by the THz band. As a result, the design and development of routing protocols in this domain must prioritize energy efficiency, communication reliability, and scalability to ensure robust data exchange across densely deployed nodes. In addition to these constraints, electromagnetic nano-networks are characterized by diverse communication requirements, driven by emerging application domains such as Software-Defined Metamaterials (SDMs), biomedical sensing, in-package wireless networks, and quantum computing systems **[21][103][107]**. These applications demand routing protocols that can effectively support data-centric communication, peer-to-peer interactions, and data dissemination across heterogeneous network scenarios.

To systematically analyze existing routing schemes and identify emerging design patterns, this chapter adopts a communication paradigm-based classification framework. This framework categorizes protocols based on their underlying communication patterns, offering a comprehensive perspective on how specific routing strategies address distinct operational objectives. By aligning protocol design with data-centric, peer-to-peer, and data dissemination communication paradigms, this classification provides valuable insights into the strengths, limitations, and research gaps within the current state-of-the-art.

The present chapter is structured as follows: **Section 3.2** outlines the research methodology employed to conduct a systematic review of routing protocols in electromagnetic nano-networks. **Section 3.3** presents the proposed Communication Paradigm-Based Classification Framework, highlighting the significance of communication paradigms as enablers of emerging application domains. **Section 3.4** provides a detailed protocol analysis, systematically examining existing routing schemes based on their communication paradigm, operational objectives, and performance metrics. Finally, **Section 3.5** synthesizes the findings, identifying key trends, open challenges, and potential directions for future research.

3.2. Research Methodology

This chapers adopts the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to ensure a structured, transparent, and reproducible review process **[88]**. 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.

3.2.1. 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")***

Fig. 3.1 below shows the simple and sophisticated (using logical AND/OR operators) query strings. Additionaly, to ensure full coverage of the relevant literature, combining automated database searches with a snowballing process **[10]**.

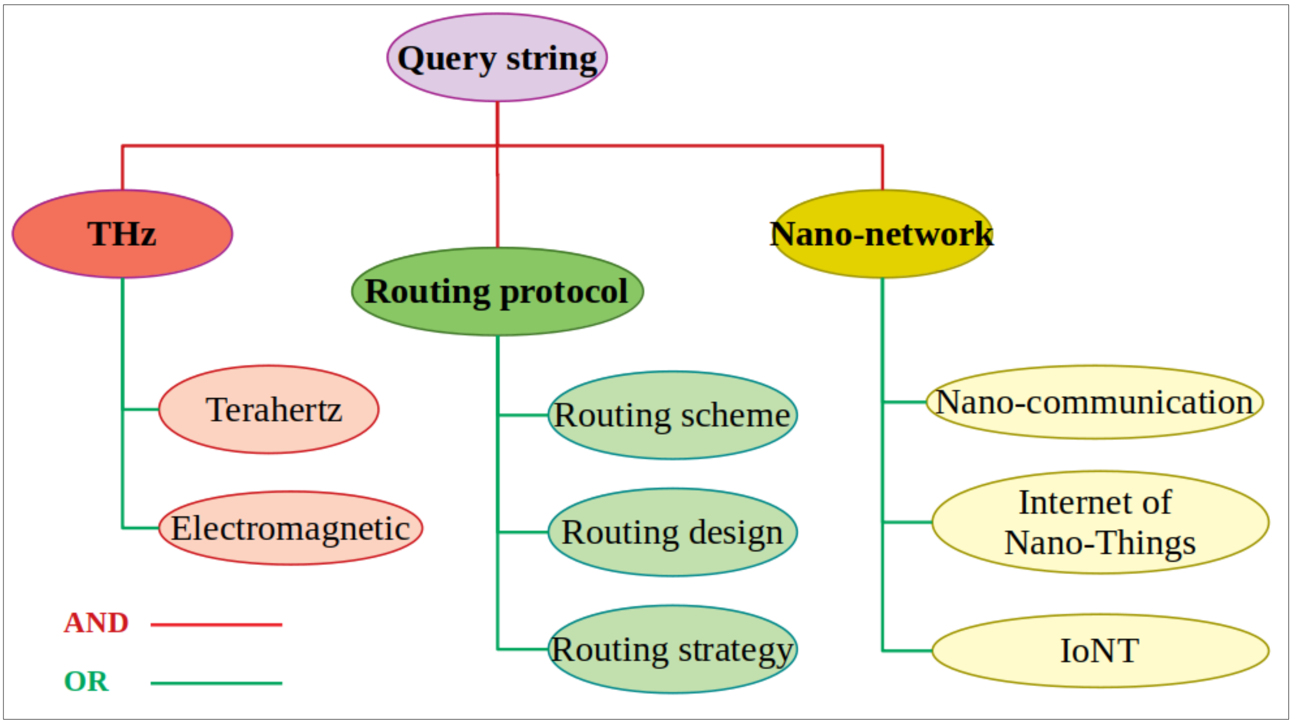


Fig. 3.1: The search hierarchy shows the straightforward and mixed search terms

3.2.2. 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 papers, which were further screened based on title and abstract relevance, and 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 papers. **U**nderwent full-text analysis, resulting in the final selection of 25 research papers that align with the research scope, as illustrated in Fig. 3.2. 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.

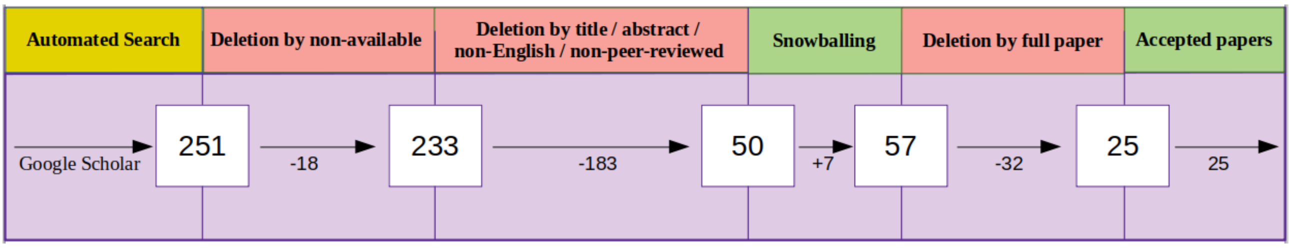


Fig. 3.2: Selection of the research papers

3.3 Communication Paradigm-Based Classification Framework

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 Fig. 3.3:

1. **Data-Centric Communication:**

Data-centric communication serves as a fundamental paradigm in nano-networks where the primary objective is to gather, aggregate, and disseminate data from multiple nodes to a central entity or sink node. This paradigm is critical in application domains where data reporting and event-driven communication are prioritized, such as environmental monitoring, biomedical sensing, and industrial control systems.

In these contexts, data-centric communication enables the network to efficiently manage data flow by aggregating redundant information, reducing transmission overhead, and optimizing resource utilization. By employing mechanisms to prioritize critical data and filter redundant packets, data-centric communication ensures that essential data is reliably delivered to the sink node, thereby minimizing energy consumption and preventing network congestion in dense deployments.

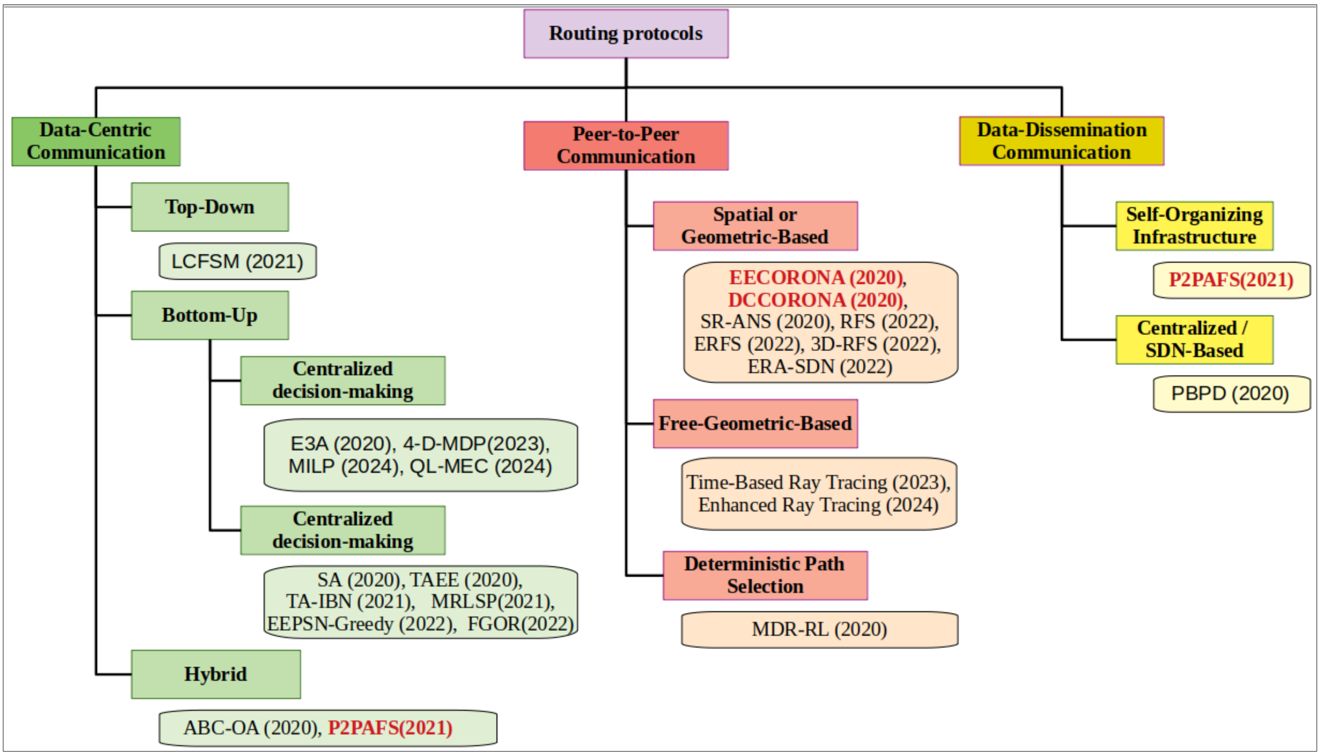


Fig. 3.3: Classification of existing routing protocols for EM nanonetworks.

2. **Peer-to-Peer Communication:**

Peer-to-peer communication is vital in nano-networks where nodes must exchange data directly with neighboring nodes without relying on a central controller. This paradigm is particularly relevant in application scenarios that demand localized coordination, distributed sensing, and direct data exchange, such as Software-Defined Metamaterials (SDMs), in-package wireless networks, and quantum computing systems.

By facilitating localised interactions, peer-to-peer communication enables nodes to collaborate in performing complex tasks, synchronise operational states, and collectively manage data transmission. This localised exchange of information is essential in scenarios where nodes must maintain consistent behaviour, share control directives, or perform distributed processing to achieve network-wide objectives. Furthermore, peer-to-peer communication minimizes latency by allowing data to be exchanged directly between nodes, reducing the reliance on centralized entities and enabling rapid decision-making in dense deployments.

3. **Data Dissemination Communication:**

Data dissemination communication focuses on the systematic propagation of data across multiple nodes, ensuring that information is effectively distributed throughout the network. This paradigm is particularly significant in scenarios involving command dissemination, firmware updates, and network-wide alerts, where data must be broadcasted to all nodes to maintain synchronized network behavior.

In dense nano-networks, data dissemination communication ensures that critical control directives, state updates, or configuration messages are consistently delivered to all nodes, despite high node density and potential communication interference. By Implementing controlled flooding or adaptive broadcasting mechanisms, data dissemination communication effectively manages network traffic, preventing broadcast storms and minimizing packet collisions. Additionally, it provides a scalable mechanism for distributing data to multiple nodes simultaneously, enabling robust data delivery in scenarios where network-wide synchronization is essential.

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. Accordingly, in the next section, this structured approach facilitates a systematic analysis of protocol design and also highlights emerging trends and key design patterns that have not been previously categorized under such a framework in nano-network literature.

3.4 Routing protocols analysis

3.4.1 Data-Centric Communication Protocols

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:

3.4.1.1 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) [82]

- **Objective:** Efficiently disseminate control commands and routing instructions from a central controller to nano-nodes using a simplified finite state machine (FSM) model, thereby minimizing memory usage and computational overhead.
- **Mechanism:**
  LCFSM employs a centralized controller to encode routing commands and control

instructions as binary sequences. Each node is equipped with a finite state machine (FSM) comprising a fixed set of states, each representing a specific action (e.g., forward, drop, wait). Upon receiving a binary sequence, the node interprets the sequence as a state transition, determining its next action without requiring complex processing or route discovery. For instance, a received binary sequence may instruct the node to forward a packet to a designated neighbor or hold the packet for a specific time interval. The FSM configuration is predefined by the controller, allowing the network to operate in a deterministic manner, with nodes executing fixed actions based on received control sequences. Periodic updates from the controller enable route reconfiguration in response to network dynamics, such as node failures or energy depletion.

- **Implementation:**
  Nodes maintain a lightweight FSM table, reducing memory overhead compared to traditional routing tables. The FSM is initialized during network deployment and updated periodically through control packets broadcast by the controller. This centralized approach ensures consistent route execution while minimizing node-level processing complexity.
- **Strengths:** Low computational overhead, minimal memory usage, deterministic routing reduces communication delays.
- **Limitations:** Static routing structure limits adaptability to dynamic network changes; reliance on centralized control may introduce latency.

3.4.1.2 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.

3.4.1.2.1 Centralized decision-making / SDN-Based:

1- Enhanced Energy-Efficient Algorithm (E3A 2020) [71]

Objective: Optimize energy consumption while ensuring reliable data transmission in Internet of Nano-Things (IoNT) networks.

Mechanism:

The E3A protocol operates through two distinct phases: the Reasoning Phase and the Learning Phase. During the Reasoning Phase, nanosensors periodically evaluate residual energy, link quality, and packet delivery ratios to determine optimal next-hop nodes. Nodes with higher energy levels are prioritized as forwarders, minimizing overall network energy consumption. The Learning Phase leverages historical data collected by Cognitive Relay Nodes (CRNs) to refine routing decisions over time, enabling the protocol to adapt to dynamic network conditions and optimize long-term performance. The hierarchical network structure includes nanosensors, nano-routers, and a central gateway, with CRNs functioning as key decision-making nodes that execute both reasoning and learning processes.

Implementation:

The protocol is implemented in a hierarchical network with nanosensors as data generators, CRNs as intermediate relay nodes, and a central gateway as the data sink. Each CRN executes the reasoning and learning processes, updating its routing table based on historical transmission outcomes and real-time network conditions.

Strengths: Adaptive path selection, energy-aware routing, hierarchical structure reduces redundant transmissions.

Limitations: The learning phase involves collecting and disseminating historical data to refine routing paths, leading to increased control overhead and energy consumption, especially under high traffic. This iterative process may also delay adaptation to sudden network changes, such as node failures or energy fluctuations.

2- 4-DMDP 2023 (Dynamic Multi-hop Routing using Markov Decision Process) [105]

- **Objective:** Enable dynamic routing in flow-guided nanosensor networks, particularly in biomedical applications with flow-driven mobility.
- **Mechanism:**
  The 4-DMDP protocol models the network as a Markov Decision Process (MDP), where each node's state is defined by parameters such as position, energy level, and event priority. The centralized controller periodically collects state information from all nodes, constructing a global network model. Using this model, the MDP agent calculates expected rewards for each action, such as forwarding to a specific neighbor or holding data until the next flow cycle. The reward function considers factors like flow velocity, node mobility, and data priority. After the training phase, the optimal Q-table is disseminated to nodes, enabling them to select next-hop nodes based on their local state and the global routing policy. The two-hop routing strategy is emphasized to mitigate communication range limitations and optimize data delivery in mobile biomedical environments.
- **Implementation:**
  Nodes periodically transmit state information to the controller, which updates the global model and recalculates optimal routing policies. The Q-table is then distributed to nodes for decentralized decision-making during runtime.
- **Strengths:** Flow-aware routing, dynamic adaptation to mobility, multi-hop communication.
- **Limitations:** Computational complexity of MDP formulation; reliance on a centralized controller for state monitoring and policy updates.

3- Mixed-Integer Linear Programming (MILP 2024) Routing Scheme [110]

- **Objective:** Minimize energy consumption by optimizing routing paths, bandwidth allocation, and sub-band assignment using a centralized optimization model.
- **Mechanism:**
  The MILP scheme operates by collecting global network data, including node positions, energy levels, and sub-band availability. The centralized controller formulates a MILP model, aiming to minimize total energy consumption while adhering to constraints related to bandwidth allocation, sub-band interference, and transmission reliability. The optimization process generates routing tables that specify paths, bandwidth allocations, and sub-band assignments for all nodes. Once computed, the routing tables are distributed to

nodes, which adhere to these predefined paths without further adaptation. This centralized approach effectively offloads computational complexity from resource-constrained nodes but may introduce latency and scalability concerns in dynamic networks.

- **Implementation:**
  The MILP model is executed at the centralized controller, which collects network state information and solves the optimization problem. The computed routing tables are then disseminated to individual nodes, specifying optimal paths and bandwidth allocations.
- **Strengths:** Comprehensive optimization, centralized decision-making reduces node-level processing overhead.
- **Limitations:** Computational complexity limits scalability; centralized control introduces potential latency.

4- QL-MEC 2024 (Reinforcement Learning for Multi-hop Energy Control) [75]

- **Objective:** Adaptively manage energy consumption and routing paths using reinforcement learning to respond to dynamic network conditions.
- **Mechanism:**
  The QL-MEC protocol leverages a Q-learning algorithm to learn optimal routing paths based on network state information, such as energy levels, link quality, and hop count. The centralized controller acts as the training environment, where each node-state is associated with a set of possible actions (e.g., forward to neighbor A, forward to neighbor B, drop packet). Rewards are assigned based on the outcomes of each action, prioritizing energy efficiency and packet delivery success. After multiple training iterations, the Q-table converges toward optimal action-state pairs, which are then distributed to nodes. Nodes independently select actions based on their local state while adhering to the globally optimized strategy defined by the Q-table.
- **Implementation:**
  The training phase is executed centrally, with the Q-table being disseminated to all nodes after convergence. During runtime, nodes use the Q-table to autonomously determine routing actions based on local state information.
- **Strengths:** Adaptive to network dynamics, learning-based decision-making, decentralized execution after training.
- **Limitations:** High computational complexity during training; reliance on a centralized controller for training may limit scalability.

<u>3.4.1.2.1 Autonomous decision-making :</u>

1- Temperature-Aware Intra-body Nano-networks (TA-IBN 2021 [85], TAEE 2020 [66], SA 2020 [67])

- **Objective:** Regulate thermal effects during data transmission in biomedical nano-networks while ensuring data delivery.
- **Mechanism:**
  The three protocols—TAEE, SA, and TA-IBN—implement distinct mechanisms to

manage thermal effects. TAEE employs a temporal data correlation mechanism to suppress redundant transmissions, reducing thermal buildup. SA uses a simulated annealing algorithm to select optimal routes based on node temperature history and data priority, balancing transmission reliability and thermal regulation. TA-IBN simplifies the process by employing a threshold-based mechanism in which overheated nodes are excluded from routing paths, preventing further thermal stress. Nodes autonomously assess their local temperature and forward data only if their temperature is below a predefined limit, preventing potential tissue damage.

- **Implementation:**
  Nodes operate autonomously, executing temperature checks and forwarding data based on predefined thresholds or probabilistic decision-making in the case of SA.
- **Strengths:** Effective thermal regulation, autonomous decision-making, adaptive routing.
- **Limitations:** Computational complexity in SA; limited scalability in TA-IBN due to path determinism.

2- Multi-hop Routing Protocol Based on Link State Prediction (MRLSP 2021) [83]

- **Objective:** Enhance data delivery reliability and energy efficiency in intra-body wireless nanosensor networks by predicting link states using a Kalman filter and refining routing decisions through fuzzy logic.
- **Mechanism:**
  MRLSP employs a predictive multi-hop routing strategy, where each node periodically estimates the quality of its links using a Kalman filter that analyzes both historical and real-time signal metrics. This predictive model enables nodes to forecast link stability and proactively select reliable forwarding paths. Once link states are predicted, nodes apply a fuzzy logic-based inference mechanism to evaluate potential next-hop nodes based on three criteria: predicted link quality, residual energy, and distance to the Nano Controller (NC). Nodes assign weights to each criterion, dynamically adjusting their forwarding decisions to balance data delivery reliability and energy consumption. To prevent excessive retransmissions, the protocol restricts forwarding to a geometrically defined candidate region, computed locally by each node based on its position and the known coordinates of the NC. Additionally, the protocol integrates an ultrasonic energy harvesting model, allowing nodes to intermittently recharge and rejoin the network, thus prolonging overall network lifetime. The multi-hop routing structure ensures data delivery to the NC through predictive path selection, mitigating the impact of link fluctuations and reducing packet loss.
- **Implementation:**
  Each node operates autonomously, executing the Kalman filter to predict link states and employing fuzzy logic to prioritize the best next-hop node. The routing decisions are made locally, without centralized control, based on dynamically updated link state predictions. The protocol also supports periodic energy harvesting to sustain nodes in low-energy states.
- **Strengths:** Predictive link state estimation enhances routing reliability, autonomous decision-making reduces control overhead, and energy harvesting mitigates node depletion.

- **Limitations:** High computational complexity due to real-time Kalman filtering and fuzzy logic evaluation; reliance on static node positions may limit adaptability in dynamic environments; potential bottlenecks if energy harvesting is insufficient to sustain nodes.

3- Energy-Efficient Protocol for Sensor Networks (EEPSN-Greedy 2022) [94]

- **Objective:** Extend network lifetime by implementing a cluster-based, energy-aware forwarding strategy that minimizes the number of active transmitters during data transmission.
- **Mechanism:**
  EEPSN-Greedy adopts a hierarchical network structure in which nodes are organized into clusters, each managed by a nanorouter. The protocol begins with a Node Discovery (ND) phase, during which each node broadcasts its residual energy to nearby nodes. The node with the highest remaining energy within a cluster is selected as the Cluster Controller (CC), responsible for aggregating data from other nodes and relaying it to the nanointerface. A greedy algorithm governs the data forwarding process, selecting the next-hop node based on proximity to the nanointerface and remaining energy levels. This selection process ensures that nodes with the highest energy are prioritized, reducing the likelihood of premature node depletion. Within each cluster, data transmission follows a single-hop strategy to minimize communication overhead, while inter-cluster communication is managed by the CCs, creating a multi-hop routing structure.
- **Implementation:**
  EEPSN-Greedy is implemented as a two-tier network, with nanonodes forming clusters around static nanorouters. The nanorouters act as CCs, managing data flow and forwarding aggregated data to the nanointerface. The protocol emphasizes single-hop communication within clusters but allows multi-hop communication between clusters.
- **Strengths:** Energy-efficient forwarding, hierarchical structure reduces redundant transmissions, cluster-based data aggregation.
- **Limitations:** Single-hop communication within clusters limits scalability in sparse networks; potential hotspot formation at cluster controllers.

4- Flow-Guided Opportunistic Routing (FGOR 2022) [92]

- **Objective:** Enhance data delivery reliability in mobile intra-body nanonetworks by exploiting flow dynamics (e.g., blood flow) to guide packet forwarding.
- **Mechanism:**
  FGOR is structured around a three-layer architecture consisting of mobile nano-nodes, static nano-routers, and a gateway. The protocol operates through two models: the Relative Position (RP) Model and the Mobility Gradient (MG) Model. The RP Model assigns each node a proximity index based on the number of hops to the gateway, allowing nodes to independently estimate their relative position within the network. The MG Model refines this index by incorporating mobility trends, prioritizing nodes moving toward the gateway to mitigate counterproductive forwarding. When a node receives a data packet, it computes its RP and MG indices, selecting the node with the highest mobility gradient and closest proximity to the gateway as the next hop. A priority-based backoff scheme regulates data

transmission, assigning shorter backoff times to nodes closer to the gateway, reducing collision probability and redundant transmissions.

- **Implementation:**
  The RP and MG indices are computed locally by each node based on periodic probe packets broadcast by the gateway. Nodes maintain local forwarding tables based on their indices, allowing them to independently select the best forwarder in real-time.
- **Strengths:** Adaptable to node mobility, flow-aware routing strategy, opportunistic multi-hop forwarding.
- **Limitations:** Dependence on accurate mobility prediction; potential delays in dynamic environments due to flow fluctuations.

3.4.1.3 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) [73]

- **Objective:** Improve data delivery efficiency in dynamic, energy-constrained nano-networks using a swarm intelligence-inspired approach that balances data relevance and residual energy.
- **Mechanism:**
  ABC-OA employs a dual-phase framework combining data smoothing and opportunistic node selection. The first phase, Exponential Weighted Moving Average for Opportunistic Data Transmission (EWMA-ODT), applies a data smoothing algorithm to reduce redundant transmissions by filtering out similar data packets based on sensed physiological data. The second phase, Artificial Bee Colony for Query Response Transmission (ABC-QRT)**,** adopts a swarm intelligence approach to optimize node selection for data forwarding. The protocol categorizes nodes into three roles: Scouts, Workers, and Soldiers. Scouts identify potential forwarders based on residual energy and link quality. Workers assess candidate nodes based on data relevance and proximity to the destination, while Soldiers execute data transmission using a fitness-driven selection algorithm that balances energy consumption and data priority. This two-phase strategy enables dynamic node selection while maintaining energy efficiency and data relevance.
- **Implementation:**
  Nodes operate autonomously during the EWMA-ODT phase, independently suppressing redundant data based on local data similarity checks. During the ABC-QRT phase, nodes engage in a query-driven node selection process, applying the ABC algorithm to identify optimal forwarders based on multi-criteria evaluation (residual energy, data relevance, link quality).
- **Strengths:** Swarm intelligence enhances node selection, data smoothing reduces redundancy, adaptive to network dynamics.
- **Limitations:** Primarily single-hop communication; increased computational complexity due to multi-criteria evaluation.

3.4.2 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:

1. **Flood-Based Communication**
2. **Deterministic Path Selection (No Flood-based)**

3.4.2.1 Flood-Based Communication Protocols:

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

3.4.2.1.1 Spatial or Geometric-Based

1- Enhanced Energy-Efficient CORONA (EECORONA 2020) [64]

- **Objective:** Extend CORONA by incorporating redundancy control and energy awareness to reduce transmission overhead and improve energy efficiency.
- **Mechanism:**
  EECORONA enhances CORONA by introducing three adaptive forwarding mechanisms:
  1. **Energy-Based Forwarding:** Nodes retransmit packets based on their residual energy, reducing the number of active forwarders.
  2. **Counter-Based Forwarding:** Each node maintains a redundancy counter, limiting the number of retransmissions per packet.
  3. **Hybrid Forwarding:** Combines energy-based and counter-based mechanisms to balance energy consumption and packet delivery reliability. Nodes monitor their residual energy and adjust their forwarding probability accordingly, allowing the protocol to dynamically reduce forwarding redundancy while maintaining delivery ratios.
- **Implementation:**
  Nodes execute energy and counter-based forwarding independently, using locally collected metrics. The hybrid mechanism adjusts redundancy thresholds based on observed network density and packet reception rates.
- **Strengths:** Reduced transmission redundancy, energy-aware forwarding, adaptable to network density.
- **Limitations:** Increased control overhead due to energy monitoring; potential communication gaps in sparse regions.

2- Distributed Cluster-Based Coordinate and Routing System (DCCORONA 2020) [63]

- **Objective:** Enhance data delivery reliability and reduce redundant transmissions in dense electromagnetic nano-networks by implementing a cluster-based, coordinate-driven routing strategy.

- **Mechanism:**

  DCCORONA builds upon the original CORONA protocol by introducing a cluster-based structure to manage data dissemination more efficiently in dense network deployments. Nodes self-assign virtual coordinates based on their relative positions, forming logical clusters based on proximity. Each cluster elects a Cluster Head (CH) using a randomized algorithm that considers residual energy and link quality. CHs act as primary forwarders, coordinating intra-cluster communication and relaying data to neighboring clusters. Within each cluster, nodes transmit data to their CH, which aggregates the collected data and forwards it to the next CH along the path to the destination. DCCORONA employs a counter-based forwarding mechanism to prevent redundant transmissions within clusters. Each node maintains a counter that limits the number of retransmissions per packet, reducing collision probability and conserving energy.

  To address potential connectivity loss, DCCORONA implements a rollback mechanism, allowing nodes to retransmit data if no acknowledgment is received from the intended forwarder. This mechanism ensures reliable data delivery even in sparse or lossy regions. Furthermore, to mitigate the "die-out" problem (where no eligible forwarder is present), cluster members can act as fallback forwarders when CHs are unavailable, maintaining network connectivity.

- **Implementation:**

  Nodes assign themselves virtual coordinates during the initialization phase, forming logical clusters based on proximity. Cluster Heads are elected periodically, and data packets are transmitted through CHs, following the coordinate-based path structure. The rollback mechanism is triggered when nodes detect transmission failures, initiating a secondary forwarding attempt by fallback nodes.

- **Strengths:** Reduces redundant transmissions through controlled flooding and counter-based mechanisms. Energy-efficient due to cluster-based structure and selective forwarding. Reliable data delivery is maintained through the rollback mechanism.

- **Limitations:** Potential communication delays in sparse networks where fallback nodes are not immediately available. Cluster formation and CH election introduce additional control overhead. Scalability may be limited in highly dynamic networks with frequent node mobility, requiring frequent CH re-election and coordinate re-assignment.

3- Scaling up Routing in Nanonetworks with Asynchronous Node Sleeping (SR-ANS 2020) [65]

- **Objective:** Mitigate congestion and reduce energy consumption in ultra-dense nano-networks by integrating a decentralized sleep scheduling mechanism with stateless routing.

- **Mechanism:**

  SR-ANS operates by integrating sleep scheduling with the Stateless Linear-path Routing (SLR) protocol to balance energy consumption and maintain network connectivity. Nodes independently enter and exit sleep mode based on local node density and observed traffic conditions. Nodes monitor neighboring node activity and dynamically adjust their sleep schedules to ensure that a sufficient number of active nodes remain to maintain network connectivity.

During active periods, nodes forward packets based on the SLR protocol, which leverages virtual coordinates to guide packet forwarding along a linear path toward the destination. If a packet encounters a sleeping node, it is temporarily buffered until the node wakes up or an alternative path is identified. To further optimize energy usage, SR-ANS employs a probabilistic forwarding mechanism, where nodes probabilistically decide whether to forward packets based on residual energy and current network density. This mechanism prevents unnecessary retransmissions, reducing collision risks and conserving node energy.

- **Implementation:**
  Nodes operate autonomously, managing their sleep schedules and forwarding decisions based on locally observed traffic and node density. The SLR protocol provides stateless routing, allowing nodes to forward packets without maintaining extensive routing tables. The probabilistic forwarding mechanism is executed locally, reducing control overhead.
- **Strengths:** Reduces energy consumption through adaptive sleep scheduling. Stateless routing minimizes memory usage and control overhead. Probabilistic forwarding reduces redundant transmissions.
- **Limitations:** Potential delays in data delivery if destination nodes are asleep. Limited scalability in sparse networks where active node density is insufficient. Packet buffering may lead to memory overflow under heavy traffic conditions.

4- Efficient Retransmission Algorithm for Ensuring Packet Delivery to Sleeping Destination Node (ERA-SDN 2022) [98]

- **Objective:** Improve packet delivery reliability in networks with asynchronous sleeping nodes by implementing a probabilistic retransmission mechanism.
- **Mechanism:**
  ERA-SDN addresses the packet delivery challenge in networks where destination nodes may be asleep when a packet arrives. Rather than implementing conventional retransmissions, the protocol adopts a selective retransmission strategy, where a subset of nodes in the destination zone is probabilistically selected to retransmit the packet based on their likelihood of being awake.

  Each node maintains **a** sleep-wake probability profile, calculated as the inverse of its average sleep duration. Nodes with higher wake probabilities are prioritized as retransmitters, ensuring that at least one node in the destination zone is likely awake to receive the packet.

  Upon detecting a sleeping destination node, the sending node selects a set of retransmitters from the destination zone. These nodes are assigned different backoff timers based on their wake probabilities, allowing the node with the highest probability to retransmit first. If the first retransmission fails, the next node in the retransmission set takes over, effectively forming a cascading retransmission sequence.
- **Implementation:**
  Nodes maintain a local sleep-wake probability table, updated based on observed sleep-

wake cycles. Upon packet transmission failure, the retransmission set is selected based on wake probabilities, and nodes initiate retransmissions based on their assigned backoff timers.

- **Strengths:** Increases packet delivery reliability in networks with asynchronous sleeping nodes. Reduces retransmission overhead by limiting retransmissions to high-probability nodes. Probabilistic retransmission reduces collision risks and conserves energy.
- **Limitations:** Increased control overhead due to wake probability calculations. Potential delivery delays in sparse networks with few active nodes. High dependency on accurate sleep-wake profiling, which may vary under dynamic traffic conditions.

5- Ring-Based Forwarder Selection (RFS 2022 [100], ERFS 2022 [99], 3D-RFS 2022 [65])

- **Objective:** Minimize redundant transmissions in ultra-dense networks by restricting forwarding to nodes located within specific spatial regions.
- **Mechanism:**
  RFS, ERFS, and 3D-RFS use a ring-based selection mechanism to control packet forwarding.
  - **RFS:** Defines a forwarding region as a concentric ring around the transmitter, selecting forwarders based on their spatial alignment with the intended path. Nodes receiving high-power control packets but not low-power ones are considered eligible forwarders.
  - **ERFS:** Enhances RFS by introducing multiple overlapping rings, each representing a separate forwarding opportunity. Nodes must be located within multiple rings to qualify as forwarders, reducing redundant transmissions.
  - **3D-RFS:** Extends ERFS to 3D networks, where forwarding regions are defined as spherical shells, allowing the protocol to adapt to spatial variations in node density. The ring-based approach leverages node position and transmission power to control forwarding, effectively limiting unnecessary retransmissions.
- **Implementation:**
  Nodes execute forwarding decisions based on received signal strength and predefined ring boundaries. Multiple power levels are used to define the rings, ensuring that only eligible forwarders participate in retransmission.
- **Strengths:** Controlled forwarding, spatially constrained retransmissions, scalable to dense networks.
- **Limitations:** High complexity in 3D networks, dependency on accurate power control, potential delays in sparse regions.

<u>3.4.2.1.2 Free-Geometric-Based</u>

1- Time-Based Ray Tracing (TBRT 2023) [104] and Enhanced Ray Tracing (ERT 2024) [109]

- **Objective:** Provide a coordinate-free, timing-based forwarding mechanism to reduce redundant transmissions in dense nano-networks.

- **Mechanism:**
  TBRT leverages the physical characteristics of Time Spread On-Off Keying (TS-OOK) modulation to determine forwarding paths based solely on packet reception timing. Nodes monitor packet reception windows and forward data only if they receive two identical bits from different upstream nodes within the same time slot, indicating collinearity with previous forwarders. ERT refines TBRT by incorporating a handshake mechanism to resolve issues such as double propagation and forwarding angle deviation. Nodes exchange control packets (RTF, CTF, FORGET) to confirm forwarding eligibility and mitigate propagation die-out. This mechanism reduces redundant transmissions while maintaining forwarding accuracy.

- **Implementation:**
  Nodes monitor packet timing and execute forwarding based on time slot alignment. The handshake mechanism ensures that only designated forwarders participate in each transmission cycle.

- **Strengths:** Timing-based forwarding reduces control overhead, coordinate-free design simplifies routing.

- **Limitations:** High synchronization precision required, fragile under multipath fading, limited scalability in dynamic networks.

3.4.2.2 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) [75]

- **Objective:** Enhance data delivery reliability in bufferless, energy-harvesting nano-networks using reinforcement learning to select optimal forwarding paths.

- **Mechanism:**
  MDR-RL employs a Q-learning algorithm to guide primary routing and deflection routing in highly dynamic networks. Each node maintains a Q-table, associating specific actions (e.g., forward to node X, deflect to node Y) with expected rewards based on energy consumption, link quality, and deflection ratio. When a primary route fails (e.g., due to node depletion), the node activates the deflection table, selecting an alternative path to prevent packet loss. This dual-table structure ensures that data is delivered even under adverse network conditions, such as buffer overflow or link failure.

- **Implementation:**
  Nodes train their Q-tables using local observations of link state, energy levels, and packet delivery outcomes. Deflection routes are updated based on periodic feedback, allowing nodes to dynamically adjust their forwarding strategies.

- **Strengths:** Adaptive routing, reliable data delivery under dynamic conditions, reinforcement learning enhances decision-making.

- **Limitations:** Computationally intensive, high energy consumption during training, potential delays during route recalibration.

3.4.2 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.

3.4.2.1 Self-Organizing Infrastructure

1- Peer-to-Peer Addressing and Flooding System (P2PAFS 2021) [84]

- **Objective:** Provide a versatile, stateless routing framework for dense nano-networks using self-assigned geo-addresses and dynamic forwarder selection, ensuring efficient data dissemination within self-organizing infrastructures.

- **Mechanism:**

  P2PAFS is primarily classified under Self-Organizing Infrastructure due to its use of the Dynamic Infrastructure (DIF) model, wherein nodes autonomously classify themselves as forwarders or passive listeners based on real-time packet reception strength and network density. This classification strategy minimizes redundant transmissions and optimizes data dissemination throughout the network.

  In the context of data dissemination, P2PAFS employs a counter-based flooding mechanism to control the number of forwarders in each region, effectively limiting unnecessary retransmissions. The DIF model dynamically adjusts the forwarder set based on packet reception quality, ensuring that only nodes experiencing strong reception act as forwarders. This approach maintains robust data dissemination in dense deployments while conserving node energy.

  While P2PAFS is categorized under the Data-Dissemination Communication class, it is inherently designed to support multiple communication modes, including:

  - **Data-Centric Communication Mode (Bottom-Up):** Nodes initiate data transmission based on sensed events, reporting data to a designated sink node or gateway. The protocol employs a counter-based flooding mechanism to control retransmissions, ensuring that only nodes with strong signal reception act as forwarders. The forwarder set is dynamically adjusted based on network density and observed packet reception rates, minimizing redundant transmissions while maintaining data delivery reliability.

  - **Peer-to-Peer Communication Mode:** Nodes establish direct data exchange with neighboring nodes using geo-addresses. Each node self-assigns a virtual address based on its relative position within the network, allowing nodes to identify nearby forwarders without centralized coordination. P2PAFS uses a dynamic infrastructure (DIF) model, where nodes autonomously determine their forwarding role (forwarder or passive listener) based on packet reception quality and node density. Nodes experiencing strong reception signals are more likely to act as forwarders, reducing collision risks and conserving energy.

- **Implementation:**

  Nodes self-assign virtual coordinates during initialization, forming logical zones that define forwarding regions. Forwarder selection is based on packet reception quality and network density, with nodes dynamically adjusting their forwarding probability based on observed reception strength. This approach allows P2PAFS to operate as a multi-mode communication framework, adapting its forwarding strategy based on the current communication context (data-centric, peer-to-peer, or data dissemination).

- **Strengths:** Multi-mode communication framework ensures data dissemination, data reporting, and peer-to-peer exchange. Adaptive forwarder selection reduces redundant transmissions and conserves energy. Stateless operation minimizes memory usage and control overhead.
- **Limitations:** Potential delays in sparse networks with low node density. Performance is dependent on accurate reception quality estimation, which may vary under dynamic network conditions. Increased control overhead in dense networks due to frequent forwarder reclassification.

3.4.2.2 Centralized / SDN-Based

1- Probability-Based Path Discovery (PBPD 2020) [72]

- **Objective:** Facilitate path discovery and command dissemination in dense nano-networks by employing a probabilistic, grid-based routing model managed by a centralized SDN controller.
- **Mechanism:**
  PBPD leverages a centralized SDN controller to partition the network area into a virtual grid composed of three-dimensional cells. Each cell may contain multiple static nano-routers acting as potential forwarders. The controller continuously monitors node positions and link quality, maintaining a probabilistic model of node presence within each cell. During path discovery, the controller calculates the probability of node presence in each cell, constructing a probabilistic routing table that specifies the most likely next-hop cells for a given source-destination pair. These tables are then distributed to nano-routers, which forward packets based on their local probability scores. Nodes located in high-probability cells are prioritized as forwarders to maximize delivery likelihood. This approach ensures that routing decisions are dynamically adjusted based on current network conditions without requiring extensive node-level processing.
- **Implementation:**
  The SDN controller maintains a global routing table, which is updated periodically based on feedback from nano-routers. Nodes operate as passive forwarders, executing the controller’s instructions without independent decision-making. This structure minimizes node-level processing but requires continuous control communication to update routing tables.
- **Strengths:** Efficient path discovery, centralized control reduces node-level processing, scalable to dense networks.
- **Limitations:** High control overhead due to frequent table updates, potential latency in highly dynamic environments.

Table 3.1: Regrouping of routing protocols based on technique used.

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.

3.5. Synthesis

The analysis presented in **Chapter 3** systematically categorizes contemporary routing protocols for electromagnetic nano-networks based on their underlying techniques and mechanisms. The proposed classification framework encapsulates a broad spectrum of routing strategies, ranging from cognitive and reinforcement learning-based approaches, predictive algorithms using Kalman filters and fuzzy logic, swarm intelligence, temperature-aware routing, to probabilistic forwarding mechanisms. This structured approach provides a comprehensive overview of existing protocols while identifying key design principles and emerging trends.

Table 3.1 consolidates these techniques, categorizing the protocols based on their dominant mechanisms and highlighting the specific techniques employed by each. By structuring the table to group protocols with similar underlying mechanisms, it becomes evident that the design of routing strategies in nano-networks is heavily influenced by the distinct constraints of nano-devices, such as limited energy reserves, minimal computational capacity, and restricted communication range. Consequently, most protocols adopt mechanisms that prioritize energy efficiency, adapt to dynamic network conditions, and mitigate the impact of severe path loss in the THz band.

A prominent trend observed in the synthesis is the reliance on centralized decision-making frameworks to optimize routing paths. This approach is particularly evident in protocols that leverage predictive and learning-based algorithms to anticipate network dynamics, adjust forwarding decisions, and balance communication loads across nodes. While these strategies effectively enhance packet delivery reliability and reduce latency, they may introduce significant computational overhead and increase protocol complexity; challenges that are particularly pronounced in dense nano-networks with thousands of nodes.

Another emerging trend is the integration of probabilistic and counter-based forwarding mechanisms, which are employed **to** control redundant transmissions, mitigate packet collisions, and conserve energy. These mechanisms are especially relevant in high-density deployments where uncontrolled flooding can rapidly deplete node energy reserves and exacerbate network congestion.

Moreover, the synthesis highlights the increasing adoption of energy-aware data dissemination methods, where nodes dynamically adjust their forwarding roles based on residual energy levels or data relevance. This approach not only optimizes energy consumption but also extends network lifetime by preventing the premature die-out of critical nodes. Thus, the communication paradigm-based classification framework not only serves as a comprehensive analytical tool for evaluating existing routing protocols but also establishes a systematic foundation for the development of next-generation protocols that address the unique communication challenges in dense electromagnetic nano-networks. This framework underscores the importance of adaptive mechanisms, predictive algorithms, and energy-efficient data dissemination as core design principles that will be further explored in the proposed routing schemes.

The findings from this synthesis provide a strategic basis for the subsequent chapters, where three novel routing schemes — EECORONA, DCCORONA, and P2PAFS — will be introduced in **Chapter 4**, **Chapter 5**, and **Chapter 6**, respectively. Each scheme is designed to address specific communication challenges identified in the analysis, targeting distinct communication paradigms to enhance energy efficiency, data reliability, and network scalability in dense, homogeneous nano-networks.

II

CONTRIBUTIONS

Chapter 4
EECORONA: Energy-Efficient Routing Protocol for 2D Networks

4.1 Introduction and Problem Definition

The advent of the Internet of NanoThings (IoNT) is set to enable unprecedented applications in diverse fields, including biomedical systems, industrial control, environmental monitoring, and advanced materials engineering. Among these applications, Software-Defined Metamaterials (SDMs) have emerged as a promising paradigm in the industrial domain. SDMs are metamaterials embedded with a network of nanocontrollers that can dynamically alter their electromagnetic behavior (e.g., cloaking, filtering, steering of light and sound) based on programmatic directives. However, achieving seamless communication among nanocontrollers in such systems remains a significant challenge due to the stringent energy constraints of nanoscale devices.

In the context of SDMs, nanonetworks must support point-to-point and multicast communication modes to ensure proper coordination of nanocontrollers. Existing routing schemes, such as CORONA [20], effectively address multi-hop communication in dense nanonetworks but do not explicitly consider the limited power supply of nanodevices. Thus, energy-efficient communication becomes a critical requirement for sustainable operation.

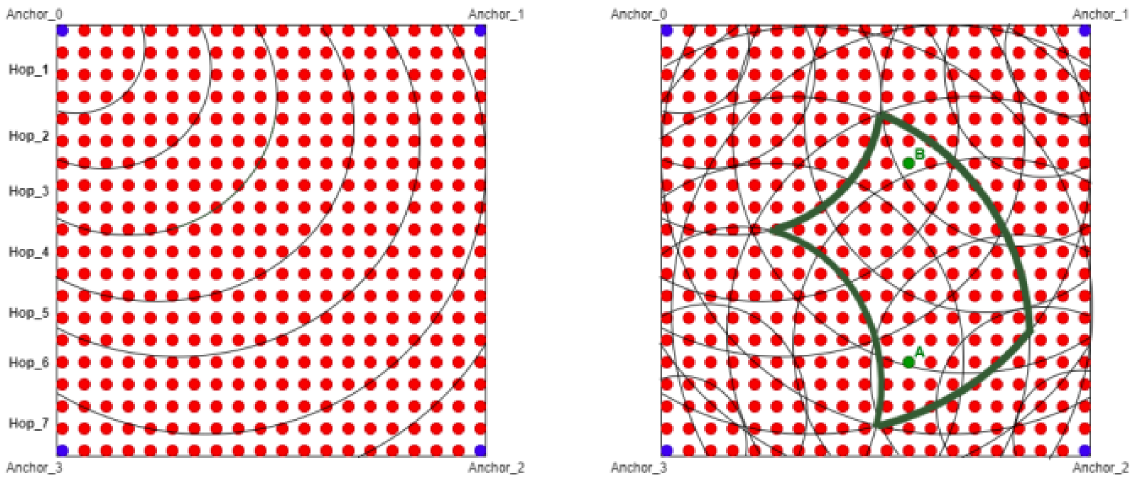
This chapter addresses this gap by presenting three proposed versions of a flood-based point-to-point routing scheme designed to optimize the CORONA protocol for enhanced energy efficiency in static and dense 2D nanonetworks. The proposed schemes introduce controlled flooding mechanisms to reduce redundant retransmissions while maintaining reliable data delivery across the network.

To the best of our knowledge, this work is the first to propose and evaluate a point-to-point routing scheme in the nanonetwork domain that explicitly considers the severe power limitations of nanodevices. Extensive simulations conducted using Nano-Sim on NS-3 [13] demonstrate the efficacy of the proposed schemes in terms of energy consumption, packet delivery ratio (PDR), and forwarding packet rate.

The chapter is structured as follows: Section 4.2, we present the coordinate geolocation address system used on CORONA scheme, because the proposed routing schemes operate on top of this system. Then, in Section 4.3, we introduces the three versions of EECORONA, detailing their design principles, algorithmic structure, and operational logic. While, Section 4.4 provides a comprehensive performance evaluation, analyzing the impact of each version on key metrics such as PDR, latency, and energy consumption. Finally, the conclusion is presented in Section 4.5.

4.2 Coordinate Geolocation Address System

The authors in [20], proposed a self-assigning address system with minimal over-head. This system operates on a rectangular area over which a large set of nanodevices is uniformly deployed, the layout may be grid or random. Four ordinary nanodevices called anchors are placed at the four vertices of this area, where the indexing of the anchors must follow a clockwise or counter-clockwise order, as shown in Fig. 4.1. Based on this order, each anchor sequentially, after a safe time-out sends a setup packet, with the SETUP flag set to 1 (i.e., a setup packet), the ANCHOR field set to its index and N HOPS field set to 1 (see Fig. 4.2a). Each receiving node realizes via the SETUP flag that the packet serves self-assigning address purposes. This node proceeds to set its N HOPS i corresponding to the given anchor i to the minimum N HOPS value over the incoming packets, then it increments N HOPS by one and retransmits the packet. Fig. 4.1a illustrates the process, where the anchor 0 starts to send a setup packet, while the arcs show the hop-based distance between the anchor 0 and each node in the nanonetwork. At concluding this process, each node in the nanonetwork sets locally its (not unique) address. The latter is composed of a set of four distance-attribute values, each corresponding to the distance between the given node and one of the four anchors. Some nodes may have the same address since they are located in the same area. The number of nodes in an area depends on: i) the nanonetwork topology type and ii) the transmission power used.



(a) Hop-based distance between the *anchor_0* and each node in the nanonetwork.

(b) Flood area limited between the node A and the node B.

Fig. 4.1: Illustration of the assigning of addresses and routing system.

4.3 Routing Phase

Based on the aforementioned addressing, the proposed schemes can route packets from the source node S with coordinates (s1, s2, s3, s4) to the destination node D with coordinates (d1, d2, d3, d4) in a flood-based manner, but only a subset of nodes whose coordinates are between those of the source and destination nodes are permitted to forward the packet. Each receiving node in the neighbor can deduce whether it should forward the received packet or not and also can determine accurately the location of the destination node, using only two of the four anchor coordinates based on ANCHOR I and ANCHOR J fields incorporated in the packet [20] (see Fig. 2b). Regarding CORONA routing process, the source node is in charge of assigning ANCHOR I and ANCHOR J fields with the indexes of the appropriate two anchors, before sending a packet. Upon receiving a packet in a node T with coordinates (t1, t2, t3, t4), the latter deduces whether it is located between the communicating nodes or not based on the criterion (4.1). If is the case, node T forwards the packet. Otherwise, it discards the packet.

$$(t_i \in [s_i, d_i]) \; and \; (t_j \in [s_j, d_j]) \tag{4.1}$$

As shown in Fig. 1b, when nodes A and B want to communicate, all nodes located in the green arc-shaped area retransmit the packets. Despite, CORONA scheme efficiently reduces the number of redundant retransmission compared to the pure flooding technique by limiting the flood area, but the latter may still maintain a large number of nodes participating in the retransmission process, leading to high-energy consumption. This sets the starting point of the present work, where we focus on reducing the number of redundant retransmissions in the limited area by applying some technique to have energy efficiency, while keeping a reasonable degree of path multiplicity to assure high communication reliability.

4.4.1 Energy-based probabilistic CORONA routing scheme

In this scheme, nodes that receive a packet retransmit it according to an energy-based probability. The operating process of this scheme involves the following steps, as summarized through the block scheme in Fig. 4.3:

1. Upon receiving a packet, each node checks whether this packet has never been treated, to avoid treating multi copies. Otherwise, the packet is simply discarded. A treated packet means that this packet has been already forwarded or discarded from this node.
2. If this packet has never been treated, the node checks whether it is located between the communicating nodes based on the criterion (4.1).
3. Then the selected nodes in the previous step retransmit the packet with the following forwarding probability:

$$P1 = \frac{E_{level} - E_{off} - E_{pkt-Tx}}{E_{max}} \tag{4.2}$$

where E level is the current energy level of the given node, E of f is the required energy level to power the node hardware, E pkt−T x is the required energy level to transmit a packet and E max is the maximum energy level.

According to the forwarding probability P 1, nodes with a higher energy level have a higher chance to forward the packet, and vice versa.

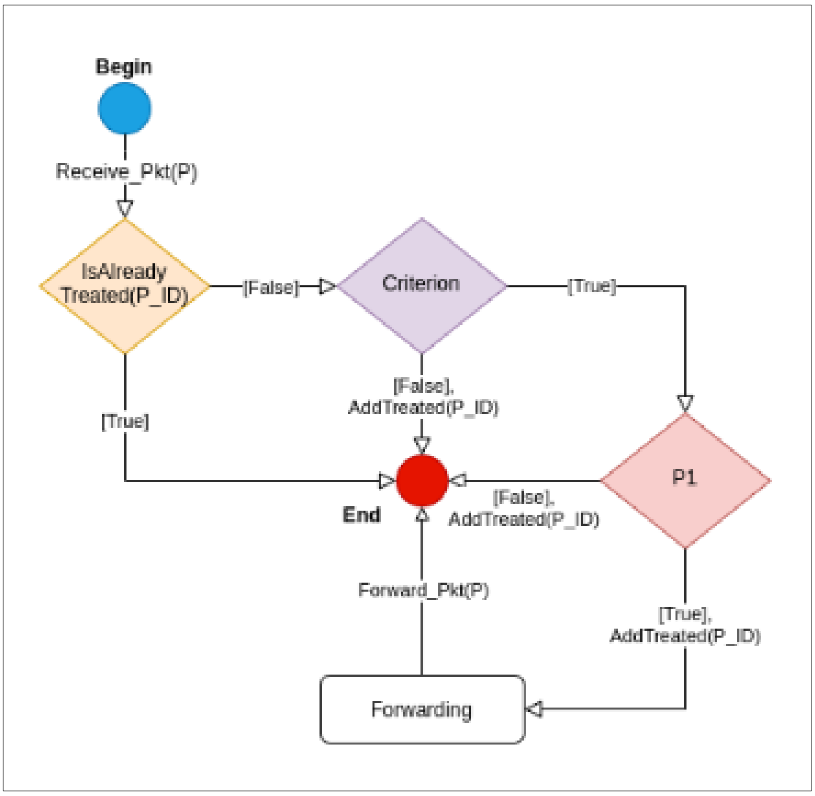


Fig. 4.2: Block scheme of the energy-based

4.4.2 Counter-based CORONA routing scheme

Despite the previous scheme could save energy by reducing redundant transmissions and receptions in the limited area between the communicating nodes, its performance may suffer from the die out problem [1], which appears when some zones in this area do not receive packets, because there is no guarantee that a packet will reach all the nodes, specifically, the destination node in our case. To avoid this problem, we propose a counter-based version. In this scheme, a node decides whether to forward a packet or not by counting the number of its copies received during a random delay, i.e., Random Assessment Delay (RAD) [22]. This scheme involves the following steps, as summarized through the block scheme in Fig. 4:

1. Upon receiving a packet, each node checks whether this packet has never been treated. Otherwise, the packet is simply discarded.
2. Then the node checks if this is the first reception of the packet. If not, the node checks if the forwarding node located in its area (has the same address that incorporated in the packet, see Fig. 2b), if is the case, a packet counter redundancy is incremented by one. The latter aims to guarantee that a packet is forwarded at least a given number of times (R) in its area. We choose R = 1, to gain the minimum number of forwarding in an area; only one node is enough to forward the packet.
3. Upon the first reception of the packet, the node checks if it is located between the source S and the destination D nodes according to the criterion (4.1).
4. If the criterion (4.1) is verified, the node delays the packet until the expiration of RAD to forward it, or until receiving the intended redundancy copies R, so the packet is discarded. The node randomly chooses RAD inside the time window t, that takes charge of the peculiarities of nanonetworks, given by:

$$t = \alpha * n * T \tag{4.3}$$

where n is the number of nodes that have the same address with the given node, that can be simply found after the end of the self-assigning address phase by exchanging HELLO packets and α is a parameter that allows adapting to the peculiarities of the used modulation technique, TS-OOK, that permits the interleaved of packets at the receiving node. Where α = 1 means there is no interleaved packets, such as in the traditional networks. Henceforth, α = 1/C, in order to tradeoff between the delay, node memory usage and number of received copies, where C is the number of interleaved packets that a node can concurrently track and process. While T is the time required to receive a packet, to decode it and to decide to forward it, given by:

$$T = \gamma * T_p + (\gamma - 1) * T_s + T_l + T_d \tag{4.4}$$

where γ is the packet size in bits, T_p is the time to transmit an electromagnetic pulse, T_s is the time between transmitting two consecutive bits, T_d is the time required to decode and decide to forward a packet and $T_l = c/d$ is the propagation time of the last bit, where c and d are the speed of light, and the communication range, respectively.

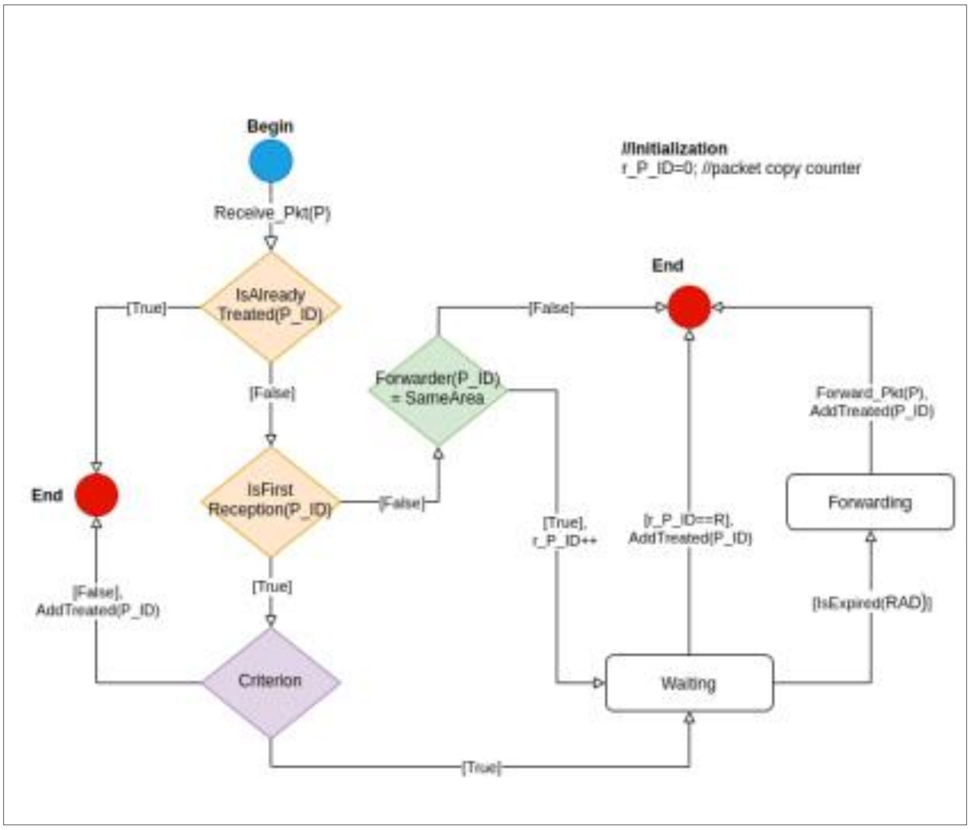


Fig. 4.3: Block scheme of the counter-based routing version.

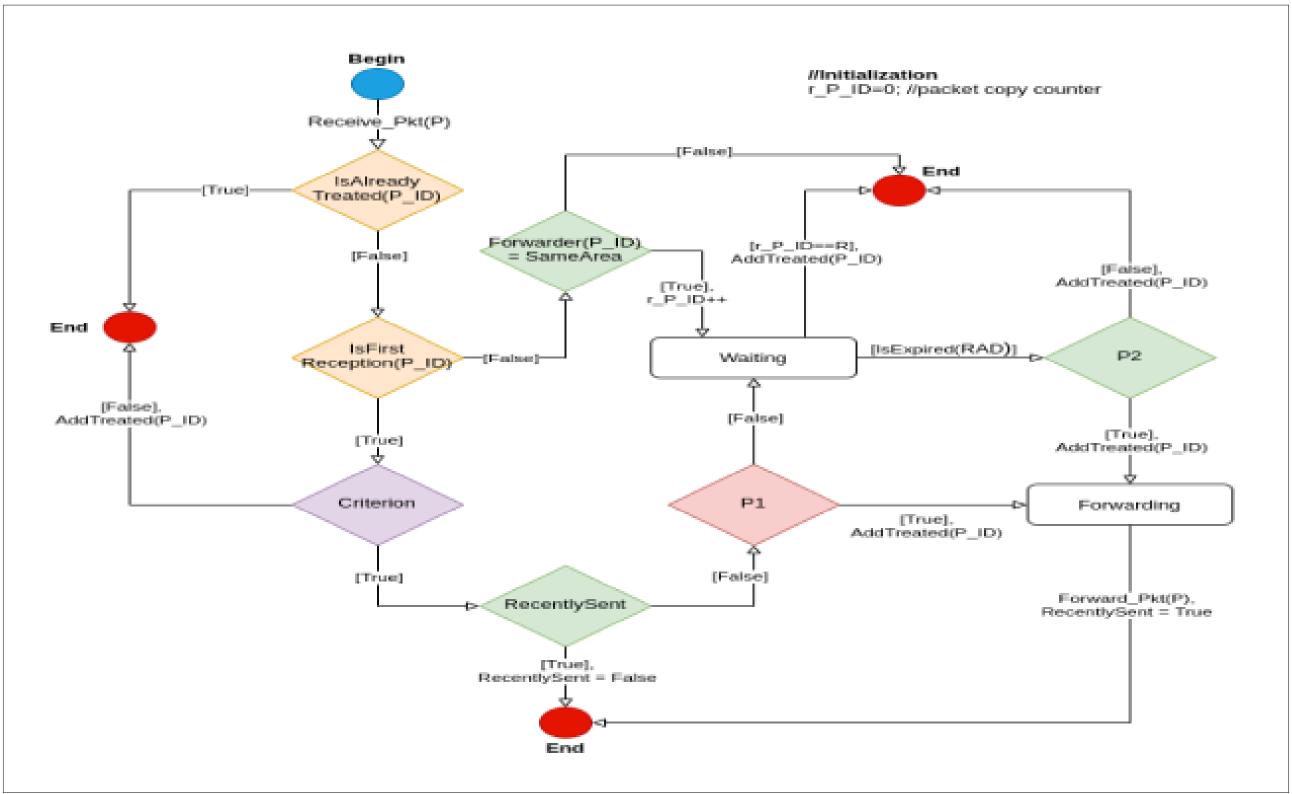


Fig. 4.4: Block scheme of the hybrid routing version.

4.4.3 Hybrid CORONA routing scheme

This version jointly applies counter-based and probabilistic flooding techniques on the nodes located in the limited area between the communicating nodes, to reduce the number of nodes that forward the packets, thus having energy efficiently performance. As summarized through the block scheme in Fig. 5, this scheme involves the following steps:

1. Upon receiving a packet, each node checks whether this packet has never been treated. If not, the packet is simply discarded.
2. Then the node checks if this is the first reception of the packet. If not, the node checks if the forwarding node located in its area, if is the case, a packet counter redundancy is incremented by one.
3. If this is the first reception of the packet, the node checks if it is located between the source S and the destination D nodes according to the criterion (4.1). If the latter is verified, the node retransmits the packet with the forwarding probability P 1. However, nodes who forwarded a packet in the last time are exempt this time, to give them more time for harvesting energy.
4. Nodes that do not forward the packet due to the forwarding probability P 1, they delay the packet until the expiration of RAD to try to transmit it again, with the forwarding probability P 2, or until receiving the intended redundancy copies R of the packet, where R = 1, so the packet is discarded. The forwarding probability P 2 is based on the number of nodes in an area, where nodes in an area that has a high number of nodes have a low chance of forwarding the packet, and vice versa. The forwarding probability P 2, given by:

$$P2 = \frac{K}{n} \tag{4.5}$$

where K is an adjusted parameter and n is the number of nodes which have the same address with the given node. According to extensive simulations, k = 1 offers the best results in terms of energy consumption and successful packet delivery rate.

4.4 Performance Evaluation

In this section, by means of extensive simulations on the nano-sim [13] open-source tool on NS-3, we evaluate the performance of the three proposed versions of an adjusted flood-based peer-to-peer routing scheme. In Section 4.4.1, we describe the evaluating metrics that have been considered in the performance evaluation, while in Section 4.4.2, we present the simulation setup and assumptions. Finally, in Section 4.4.3, we exhibit and discuss the obtained results.

4.4.1 Evaluating Metrics and Performance Scenarios

At the end of 100 cycles for each simulation, the following evaluating metrics are logged against the increasing of the packet inter-arrival time and the increasing of the nanonetwork density:

1. **Packet Delivery Ratio (PDR):**

$$PDR = \frac{NbrSuccPkt}{NbrPkt} \tag{4.6}$$

where N brSuccP kt and N brP kt are the number of packets successfully arrived to the destination node, and the total number of packets generated in the nanonetwork, respectively.

2. **Average Ratio of Forwarders (ARF)**: represents the average ratio of forwarder nodes that participate for a successful packet devilry:

$$ARF = \frac{\frac{GlobalPkt}{PDR}}{NetSize} \tag{4.7}$$

where GlobalP kt and PDR are the number of packet forwarding operations in the whole network per simulation and the packet delivery ratio for a given simulation, respectively. While N etSize is the nanonetwork size.

$$ARE = \frac{\sum_{i=1}^{NbrPkt} are_i}{NbrPkt} \tag{4.8}$$

where are i is the average residual energy in the nanonetwork after the i-th communication and N brP kt is the total number of packets generated in the nanonetwork.

3. **Average Residual Energy (ARE):**

$$ARE = \frac{\sum_{i=1}^{NbrPkt} are_i}{NbrPkt} \tag{4.9}$$

where are i is the average residual energy in the nanonetwork after the i-th communication and N brP kt is the total number of packets generated in the nanonetwork.

4.4.2 Simulation Setup and Assumptions

The present study considers uniform regular grid 2D topologies, with Xcm spacing, where X varies according to the corresponding performance scenario. The regular grid layout is considered due to its direct applicability to the smart meta-material applications (e.g., SDMs), where each node represents a nanocontroller **[21].** The selected layouts fill a fixed rectangular area with 1600 identical nanonodes. The harvesting energy mechanism of nanodevices is based on the vibration generated by the vents of the air conditioning system of a room, where the vibration frequency f , 1/t cycle = 50 Hz [9]. In line with [4], the nanonetwork settings and communication-related parameters are summarized in Table 1. It should be mentioned that each value in the figures of Section 4.3 represents the average value of 50 values obtained by 50 simulations. In each simulation, a series of 100 operation cycles take place, in each one, the source and the destination nodes are selected randomly. The error bars of the figures represent the 95% confidence intervals, to give greater reliability to the results obtained.

4.4.3 Results and Analysis

1. Varying the packet inter-arrival time

The average residual energy in the nanonetwork, the average ratio of nodes that participate for successful packet devilry and the packet delivery ratio are presented over an increase of the packet inter-arrival time in Fig. 4.5, Fig. 4.7 and Fig. 4.9, respectively. Overall, the increase of the time between the transmission of two consecutive packets offers more time to the nanodevices to harvest more energy, which increases the global residual energy in the nanonetwork, thus increasing of the successful packet delivery ratio, as shown in Fig. 4.5 and Fig. 4.9. The counter-based CORONA scheme shows the best performance in terms of residual energy. Due to its routing mechanism that aims to reduce the number of participating nodes for the retransmission process as confirmed in Fig. 4.7, where only one node in each area is enough to forward the packet. In contrast, CORONA scheme shows the worst performance in terms of residual energy, because for each communication all nodes between the communicating nodes forward the packet.

While the participating rate of nodes in the retransmission process, for the probabilistic CORONA and the hybrid CORONA schemes increases at a slight rate with the increase of the packet inter-arrival time, i.e., the increase of residual energy, due to the used forwarding probability P 1, where the higher energy level, the higher chance to forward the packet, see Fig. 4.7.

Table 4.1: Simulation Parameters.

Parameter	Value
Frequency	0.1 THz
Pulse energy	100 pJ
Pulse duration	100 fs
β: TS-OOK time spread ratio	100
SNR	10 dB
Communicating range	1 cm
Nanonetwork size	1600
t_{cycle}: harvesting cycle time	20 ms
Packet payload size	100 $bits$
Node packet information queue length	20
C: number of interleaved packets	5
Scenario 1	
Packet inter-arrival time (ms)	50, 100, 150, 200, 250, 300, 350
X: spacing (cm)	0.125
Scenario 2	
Packet inter-arrival time (ms)	300
X: spacing (cm)	0.166, 0.142, 0.125, 0.111, 0.1

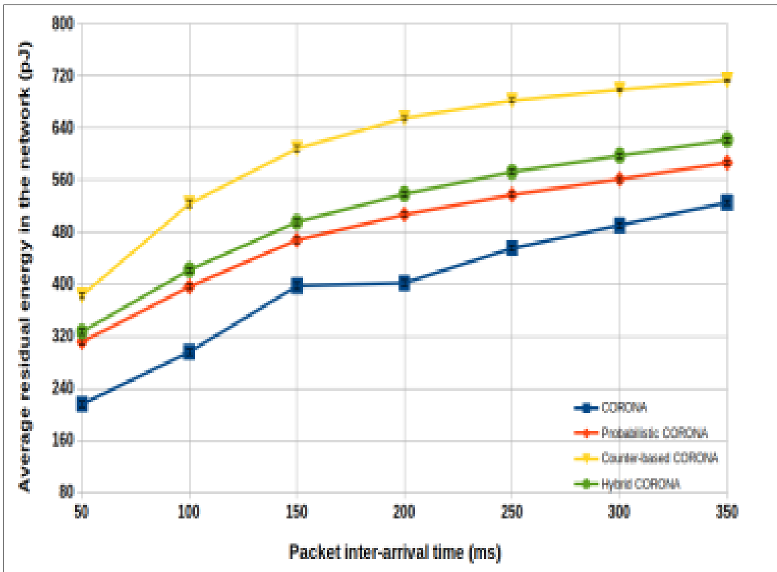


Fig. 4.6: Average Residual Energy imposed by the compared schemes, versus the packet inter-arrival time.

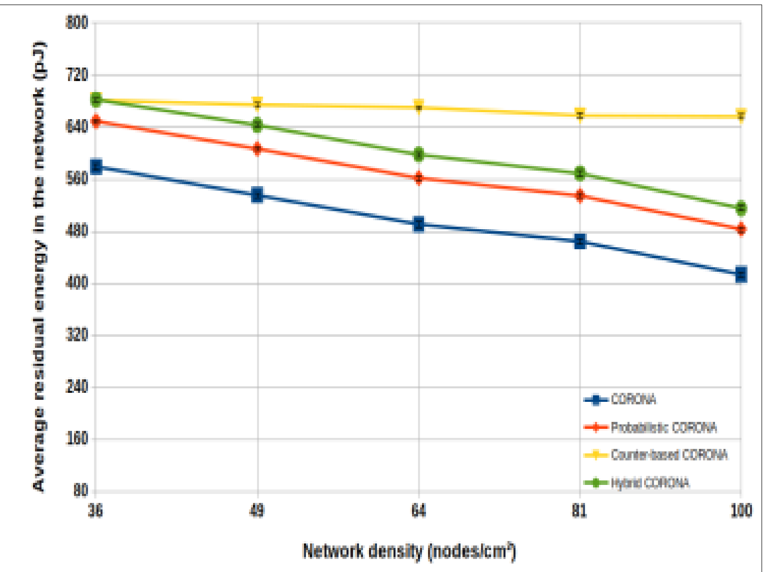


Fig. 4.5: Average Residual Energy imposed by the compared schemes, versus the nanonetwork density.

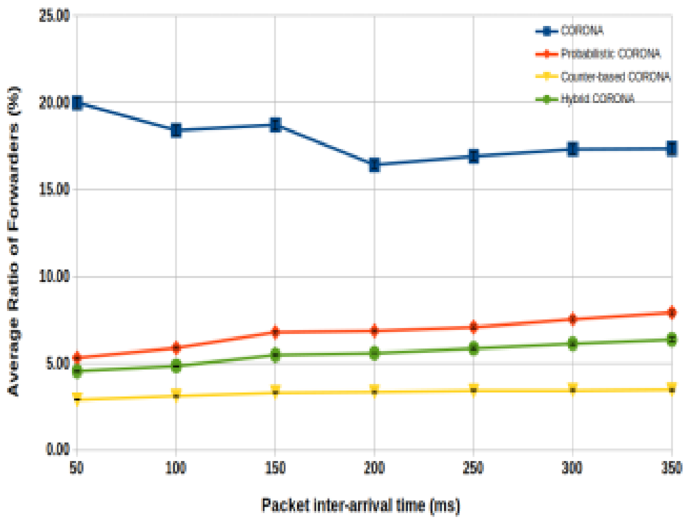


Fig. 4.10: Average ratio of forwarders imposed by the compared schemes, versus the packet inter-arrival time

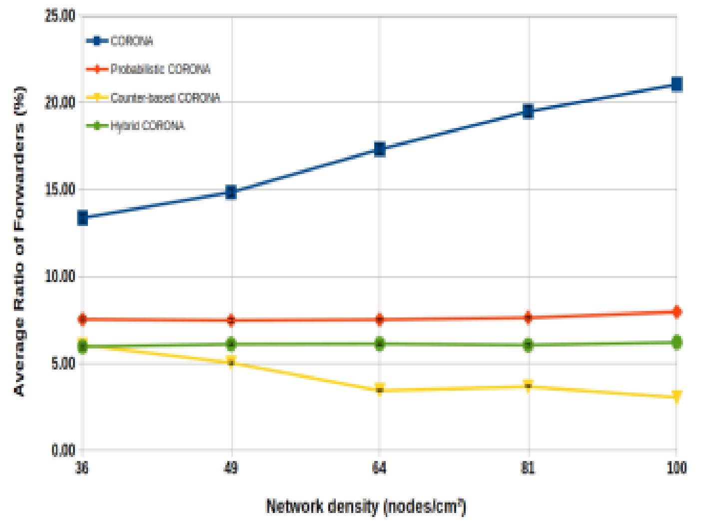


Fig. 4.9: Average ratio of forwarders imposed by the compared schemes, versus the nanonetwork density.

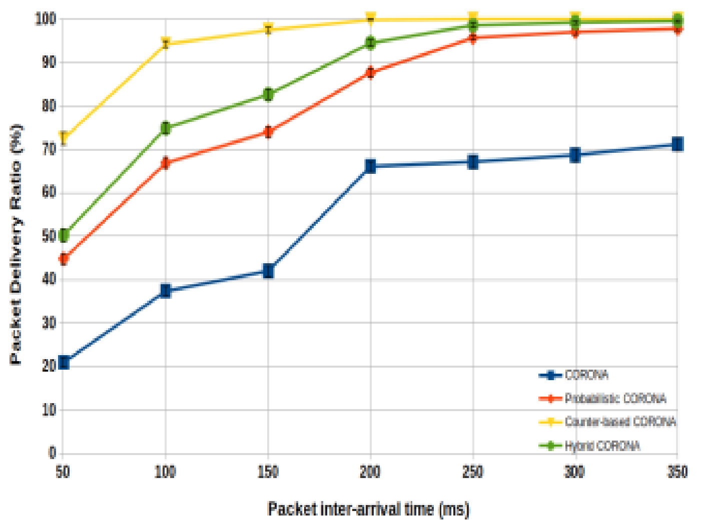


Fig. 4.8: Packet delivery ratio imposed by the compared schemes, versus the packet inter-arrival time.

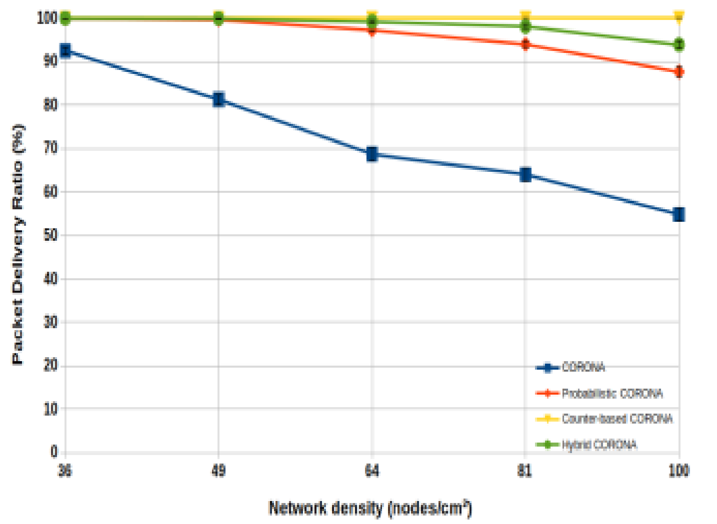


Fig. 4.8: Packet delivery ratio imposed by the compared schemes, versus the nanonetwork density.

2. Varying the nanonetwork density

The average residual energy in the nanonetwork, the average ratio of nodes that participate for successful packet devilry and the packet delivery ratio are presented over an increase of the nanonetwork density in Fig. 4.6, Fig. 4.8 and Fig. 4.10, respectively. Fig. 4.6 shows that, the larger the nanonetwork density, the more large number of nodes located between the communicating nodes, resulting in high energy consumption. For most schemes, the high energy consumption is due to the high rate of retransmission of packets and the high overhearing, as shown in Fig. 4.8. CORONA scheme has the worst performance in terms of the rate of nodes that forward the packet, where it has the higher rate with a significant increase over the increasing of the nanonetwork density. While the rate of nodes that forward the packet for the probabilistic CORONA and the hybrid CORONA schemes not affected with the increase of the nanonetwork density because the routing mechanism of these schemes not directly depend on the nanonetwork density, see Fig. 4.8. In terms of communication reliability, as shown in Fig 4.10, the counter-based CORONA scheme offers a successful packet delivery ratio up to 100% regardless of the nanonetwork density. While the probabilistic CORONA and the hybrid CORONA schemes show slight decreases over the increasing of the nanonetwork density, due to the die out problem and the increase of collision rate.

4.5 Conclusion

In this chapter, we introduced EECORONA, an energy-efficient routing protocol specifically designed for dense and static 2D nanonetworks. The proposed scheme addresses the critical challenge of energy consumption in electromagnetic nanonetworks, where traditional uncontrolled flooding protocols lead to excessive retransmissions and significant energy waste. To mitigate these issues, we developed three versions of the EECORONA protocol: Energy-Based Probabilistic CORONA, Counter-Based CORONA, and Hybrid CORONA. Each version incorporates distinct strategies to reduce redundant retransmissions while maintaining high packet delivery reliability.

The proposed routing protocols were evaluated using the Nano-Sim simulation tool on NS3, under various scenarios, including varying packet inter-arrival times and different network densities. The evaluation metrics included Packet Delivery Ratio (PDR), Average Residual Energy (ARE), and Average Ratio of Forwarders (ARF). The simulation results demonstrated that the proposed schemes significantly improve energy efficiency while maintaining acceptable communication reliability compared to the conventional CORONA scheme.

Among the three versions, the Counter-Based CORONA scheme consistently showed superior performance in terms of energy conservation, owing to its dynamic adjustment mechanism that adapts retransmissions based on the number of received packets. This adaptive strategy minimizes redundant transmissions, particularly in high-density scenarios, while effectively preventing the die-out problem that can compromise packet delivery. Consequently, the Counter-Based version proved to be the most reliable, achieving near-optimal PDR even as network density increased. The Energy-Based Probabilistic CORONA scheme also demonstrated improved energy efficiency compared to the original CORONA protocol, thanks to its energy-aware forwarding mechanism that prioritizes nodes with higher residual energy for retransmission. However, its performance varied with network density, as higher densities led to an increased collision rate, slightly affecting PDR. The Hybrid CORONA scheme balanced the strengths of both probabilistic and counter-based approaches, offering a trade-off between energy efficiency and communication reliability. This version demonstrated consistent performance across different scenarios, making it a viable option for moderately dense networks where both energy savings and reliable delivery are critical.

The comprehensive analysis highlights that EECORONA, in its various versions, represents a significant advancement over traditional flooding-based routing protocols for electromagnetic nanonetworks. The adaptive mechanisms employed by each version enhance the balance between energy conservation and reliable communication, making the protocol suite suitable for various applications, including Software-Defined Metamaterials (SDMs).

Future work will focus on extending the evaluation of EECORONA under more dynamic conditions, including mobile nodes and variable energy harvesting rates. Additionally, exploring more sophisticated adaptive algorithms to optimize the forwarding probability and delay parameters will further enhance the protocol’s robustness and efficiency.

Chapter 5
DCCORONA: Cluster-Based Multi-Hop Routing

5.1 Introduction and Problem Definition

In the previous chapter, we introduced EECORONA, a set of flood-based point-to-point routing schemes designed to enhance energy efficiency in dense 2D nanonetworks through probabilistic, counter-based, and hybrid forwarding mechanisms. While EECORONA effectively reduces redundant transmissions in flat, peer-to-peer communication, it lacks a hierarchical structure that could further optimize routing in dense deployments. To address this gap, this chapter presents DCCORONA (Distributed Cluster-Based Coordinate and Routing System for Nanonetworks)**,** a cluster-based multi-hop routing protocol that leverages cluster heads (CHs) to regulate packet forwarding and reduce energy consumption.

To the best of our knowledge, DCCORONA represents the first distributed cluster-based multi-hop point-to-point routing scheme specifically designed for 2D dense homogeneous nanonetworks. Unlike existing cluster-based schemes that primarily focus on data aggregation in sparse, heterogeneous networks, DCCORONA targets peer-to-peer communication, enabling direct interaction between any two nodes within a dense deployment. This approach is particularly relevant in application domains such as Software-Defined Metamaterials (SDMs), biomedical sensor networks, and industrial monitoring systems, where localized, energy-efficient peer-to-peer communication is critical. By implementing controlled flooding through CHs and selected cluster members (CMs), DCCORONA aims to balance communication reliability and energy efficiency while maintaining scalability in dense nanonetworks.

This chapter is structured as follows: **Section 5.2** presents the architectural framework of DCCORONA, outlining the self-addressing scheme, cluster formation process, cluster head election mechanism and the routing process. **Section 5.3** provides a comprehensive comparative analysis of DCCORONA against existing routing protocols, including EECORONA, focusing on the same key QoS metrics evaluated in the previous chapter with the addition of Average End-to-End Delay (AE2ED) as a new metric to assess latency performance. Finally, **Section 5.4** concludes the chapter, summarizing the key findings and identifying potential areas for further optimization.

5.2 Cluster Head Selection and Communication Strategy

This section presents the proposed self-addressing point-to-point distributed cluster-based multi-hop routing scheme for dense homogeneous nanonetworks. Generally, all existing cluster-based routing schemes in traditional networks or nanonetworks have the same main phases: i) cluster establishment and ii) cluster maintenance. However, the series of basic steps involved in such phases vary according to the conceptual rules of each scheme. Our scheme's steps are ordered and described as follows:

5.2.1 Self-addressing and Clusters Construction

As mentioned above, assigning a unique address for each node in such dense and constrained-resources networks is not a trivial process. Liaskos et al. proposed a lightweight computational and less overhead control packets system allowing self-assigning address **[20]**. In their work, after broadcasting four control packets, each nanodevice sets locally its not unique geo-address. Accordingly, the proposed approach constructs the clusters based on this observation, where nanodevices that share the same geo-address are affiliated to the same cluster. As illustrated in Fig. 5.1, the self-assigning system operates on a large set of nanodevices, which are uniformly deployed over a rectangular area with a layout that may be grid or random. The four nanodevices placed at the four vertices of this area have a clockwise or counter-clockwise order, so-called anchors. According to this order, the involved steps are done as follows:

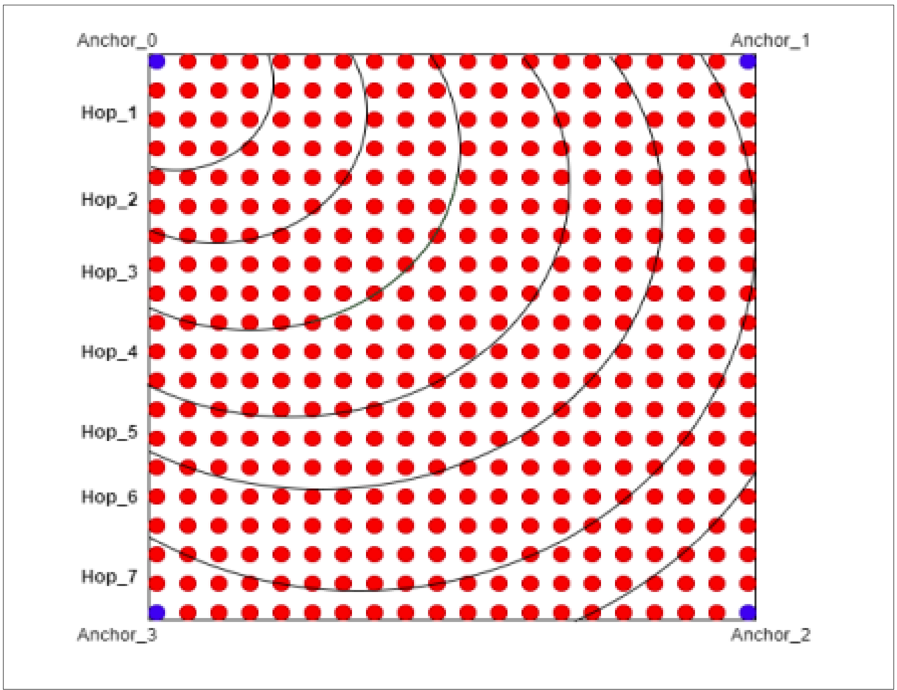


Fig. 5.1: Illustration of the self-assigning addresses.

1. Each anchor sequentially, after a safe time-out generates a cluster Construction packet (see Fig. 5.2) by setting the ANCHOR field to its index and the N HOP S field to 1, and then broadcasts it.

2. Upon reception of a packet, each node X realizes via the SET U P f lag that the given packet is for the self-assigning address purpose. Consequently, this node sets its hop-count distance to the given anchor$_i$ (X $_I$) to the minimum N_HOPS value over the incoming packets.
3. Then, node X increments the N HOP S field's value and forwards the packet. As shown in Fig. 5.1, the arcs represent the hop-count distance between each nanodevice and the anchor$_0$.

At the end, each node knows its address that is composed of four attributes; each one corresponds to the hop-count distance between this node and one of the four anchors. Nodes located in the same area share the same address; thus, they are affiliated to the same cluster (see Fig. 5.3). The number of nodes located in the same area depends on i) the nanodevice transmission power and ii) the network layout .

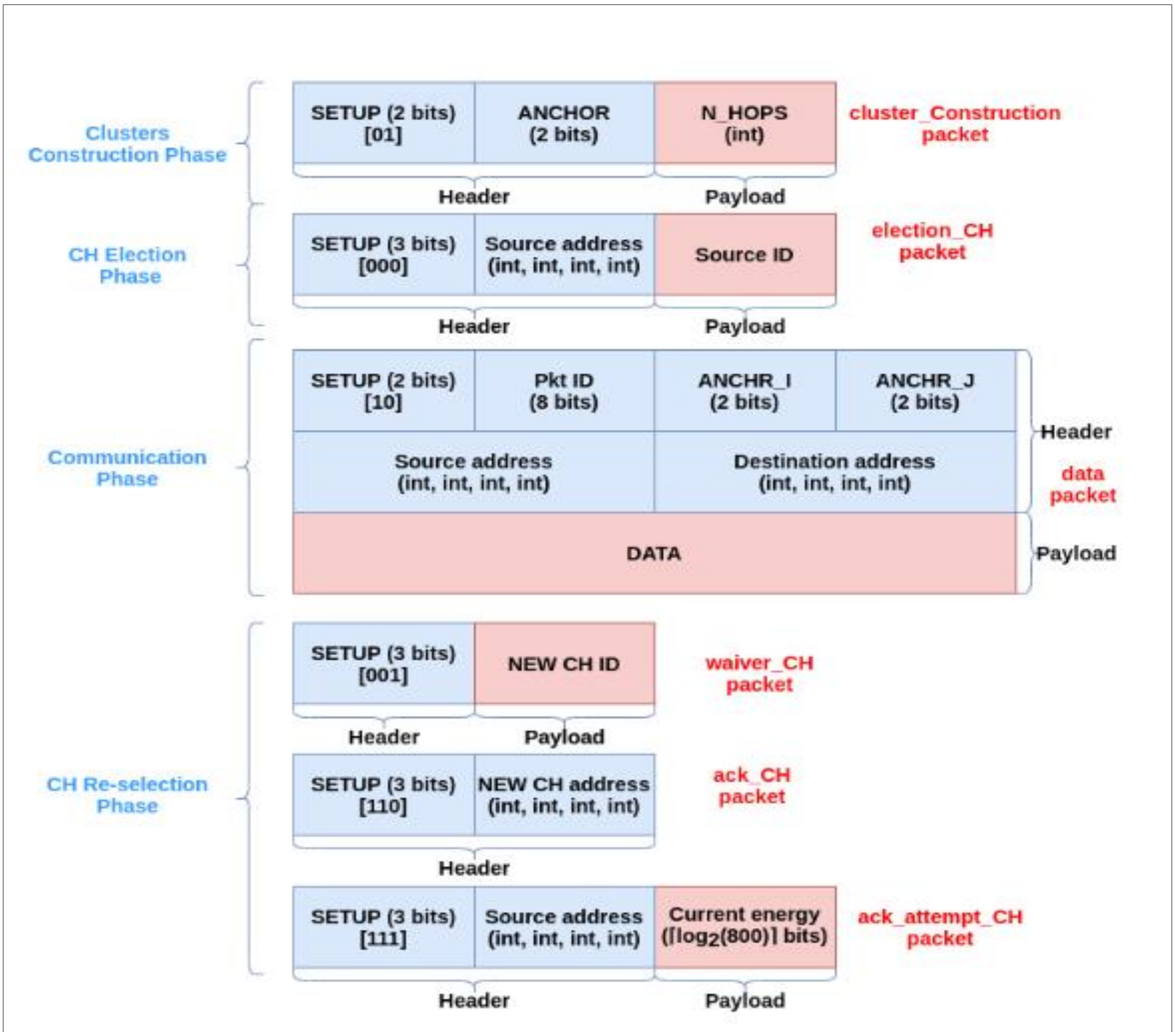


Fig. 5.2: Structure of all packets used in the proposed scheme.

5.2.2 Cluster Head Election

At the end of the self-assigning address and the self-cluster affiliation, and since we are still in the network construction phase, all nanodevices have fully charged batteries. Therefore, the election of the cluster head (CH) for each cluster in the first cycle is based on a randomly generated ID, where the nanodevice that generated the largest ID in the cluster is elected as CH. The involved steps of the CH election process are done as follows:

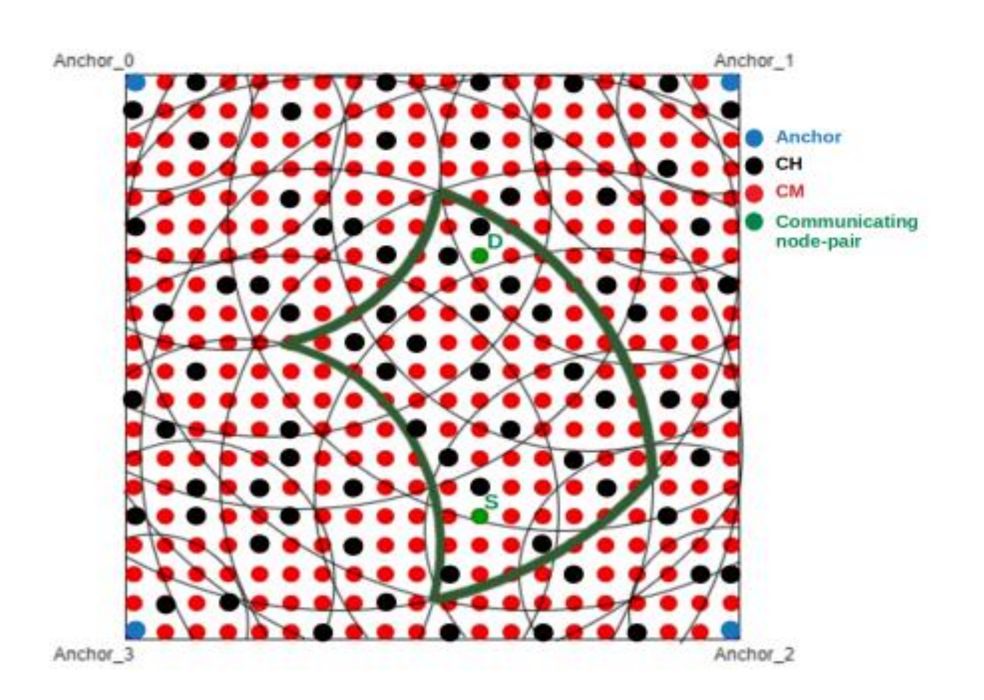


Fig. 5.3: Illustration of the node affiliation and routing process.

1. Each nanodevice generates a random value (ID).
2. Each node generates and broadcasts an election CH packet (see Fig. 5.2) after a random time-out.
3. Upon reception of an election CH packet, the receiving node applies the **Algorithm 1**.

Algorithm 1: Cluster Head Election

```
Input: MyAdr, MyID /* the node's address and ID,
    respectively                                          */
Output: CH, SuccNode /* the node's state and the ID of its
    successor in a virtual circle, respectively           */
Local: CH, SuccNode
/* Initialisation                                         */
CH ← true;
SuccNode ← -1;
/* Election                                               */
Upon receiving election_CH do
begin
    if election_CH.SrcAdr == MyAdr then
        if MyID < election_CH.SrcID then
            CH ← false;
            if SuccNode > election_CH.SrcID or SuccNode < MyID then
                SuccNode ← election_CH.SrcID;
            end
        else if CH == true then
            if SuccNode > election_CH.SrcID then
                SuccNode ← election_CH.SrcID;
            end
        end
    end
end
```

At the end of this process, for each cluster:

1. A cluster head has been elected for the first election cycle.
2. Each nanodevice knows its state (Cluster Head (CH) or Cluster Member (CM)) for the first cycle.
3. The nanodevices (CH and CMs) are arranged in a virtual circle.
4. Each CM knows its successor in that circle, which is the nanodevice that generated the smallest ID greater than its ID. While CH's successor is the nanodevice that generated the smallest ID.

5.2.3 Routing Process

On top of the addressing mentioned above, the proposed scheme allows to route packets from the source node S with coordinates (S_1, S_2, S_3, S_4) to the destination node D with coordinates (D_1, D_2, D_3, D_4), without the need of using routing tables. It is done using only the information incorporated in the packet and node-local information. As mentioned in **[20]**, in a 2D rectangular area, two anchors distances are sufficient to accurately located each node in this area. Accordingly, before to broadcast a data packet (see Fig. 5.2), the node S chooses the two anchors (ANCHOR_I and ANCHOR_J), that minimize the distance to node D, given by [11]:

$$(ANCHOR\_I, ANCHOR\_J) = \{(I, J) \\ / \ min(|S_I - D_I|), min(|S_J - D_J|), J = (I+1)\%4\} \tag{5.1}$$

Upon receiving a data packet at each neighbor nanodevice, the packet is checked whether it has been treated to avoid route loops. A treated packet is a packet that has already been forwarded or discarded from this nanodevice. If this packet has never been treated, each nanodevice forwards this packet according to its state, as summarized in Fig. 5.5. Otherwise, the packet is simply discarded. Each CH:

1. Checks whether it is located between the communicating node-pair using the following criterion (i.e., all CHs located in the green arc-shaped area in Fig. 5.3):

$$(CH_I \in [S_I, D_I]) \, and \, (CH_J \in [S_J, D_J]) \tag{5.2}$$

2. If it is the case, it simply forwards the received packet. Otherwise, the packet is discarded.

Relying only on CHs to forward packets, significantly reducing redundant retransmissions. However, it offers no guarantee that the network connectivity is satisfied, i.e., every two CHs affiliated to two neighbor clusters can communicate directly. To avoid this drawback, so-called the die out problem **[1]**, the CMs located between the communicating node-pair participate in the forwarding process by applying a counter-based forwarding mechanism. Thus, each CM decides whether to forward a packet or not by counting the number of this packets copies received during a random delay (RAD). If the RAD expires and the given CM does not receive the intended redundant copies (R) of the packet, the CM forwards it. Otherwise, this packet is discarded. We choose R = 2 to assure the minimum number of forwarding in a cluster, by supposing that the first copy of a packet is from a neighbor cluster, while the second copy is from the given cluster. Since nanodevices are equipped with restricted memories and the communication delay is an important metric in SDM applications, the proposed scheme offers a trade-off between these challenges by exploiting the peculiarities of the used modulation technique, TS-OOK; a packet is received bit by bit. Accordingly, without the need to wait receiving all the packet, CM needs to receive only the first 10 bits of each packet (SET U P and P kt ID fields), to verify if this is the first reception of this packet. If it is not the case, the corresponding counter copy (r) of this packet is incremented.

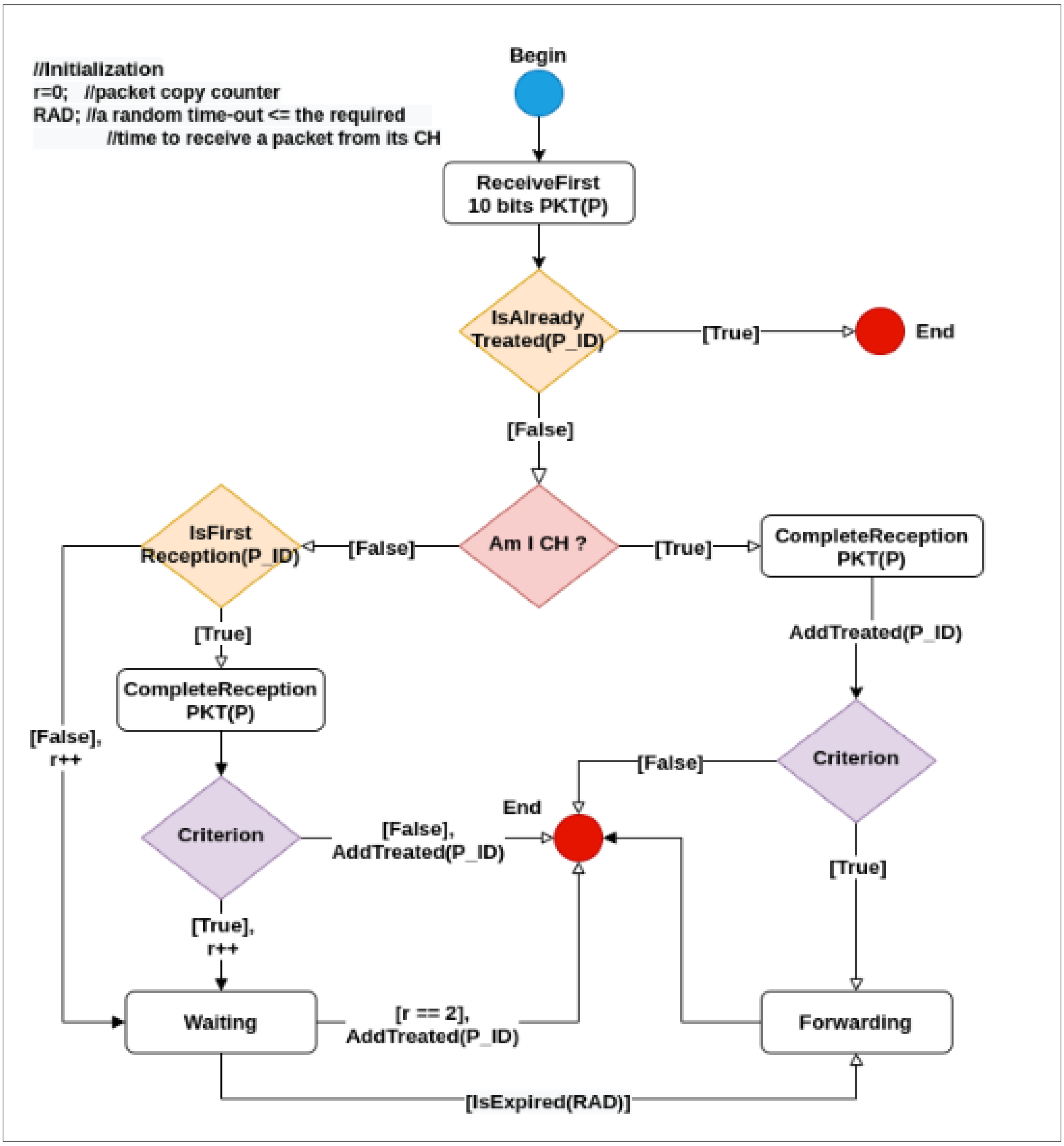


Fig. 5.4: Block scheme of the proposed routing scheme.

5.2.4 Maintenance Phase

A cluster heads re-selection phase is needed, to give current CHs more time for harvesting energy, and to avoid temporary loss of network connectivity. As **Algorithm 1** organizes each cluster's nanodevices in a virtual circle and each nanodevice knows its successor, the current CH for each cluster selects the next CH in a round-robin manner. As summarized in Fig. 5.5, the involved steps, according to the nanodevice state, are done as follows:

For each CH:

1. After each communication process, CH checks whether it has enough energy for future communication.
2. If it is not the case, CH broadcasts a waiver CH packet (see Fig. 5.1) containing the ID of its successor.
3. Upon reception of an ack CH or ack attempt CH packet (see Fig. 5.1), this CH changes its state from CH to CM.

For each next CH (current CH's successor):

1. Upon reception of a waiver CH packet, CM deduces that it is likely the next CH since the embedded ID is its own.
2. If this CM has enough energy for future communication, it replies by broadcasting an ack CH packet, as well as it changes its state from CM to CH. Otherwise, it does nothing.

For each other CM:

1. Upon reception of a waiver CH packet, CM deduces that it is not the next CH.
2. CM waits for a random time-out before attempting to be the next CH by broadcasting an ack attempt CH packet containing its current energy level.
3. If this CM receives an ack CH or ack attempt CH packet that contains an energy level greater than its energy level, this CM cancels the attempt to be the CH for the next cycle

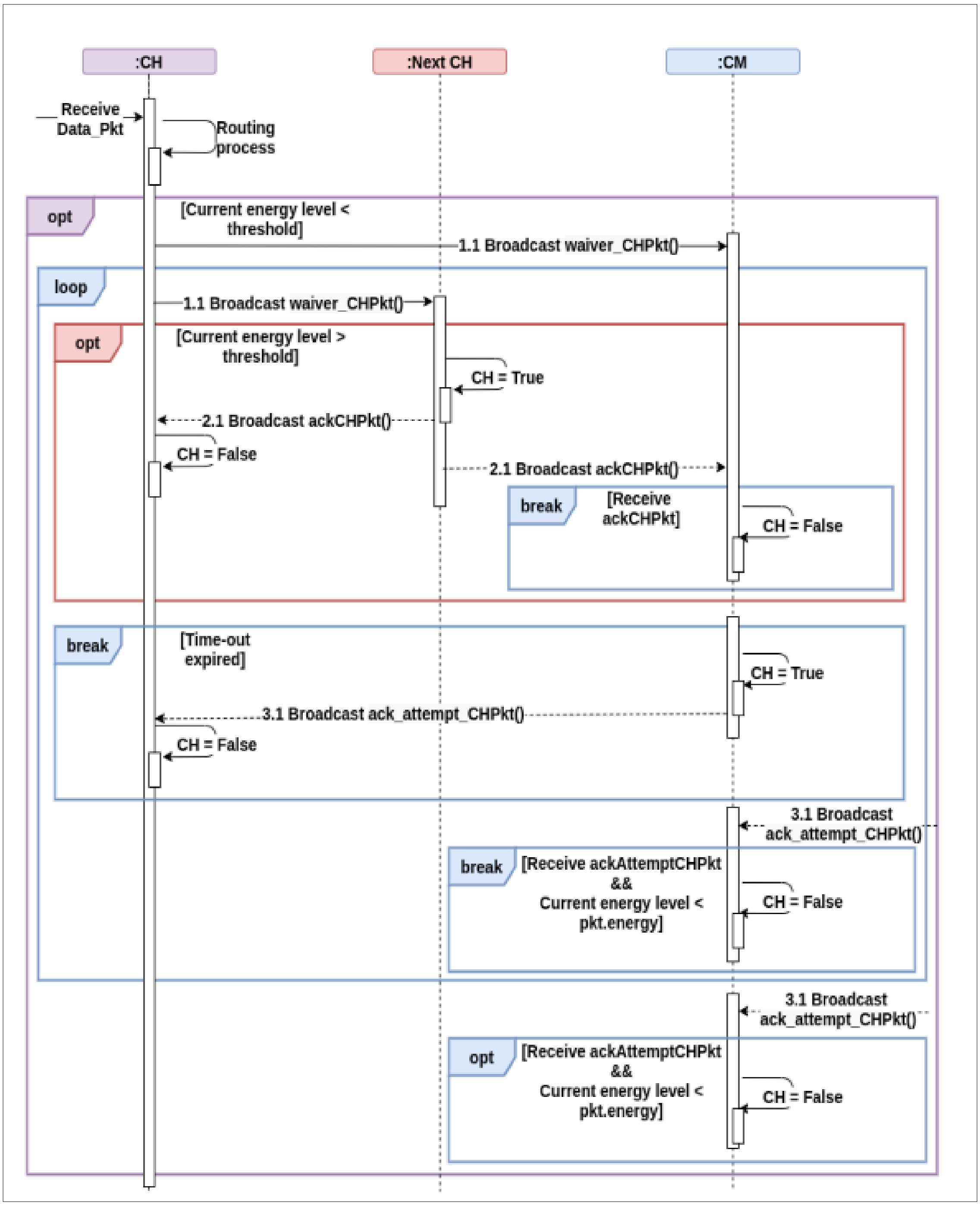


Fig. 5.5: Sequence diagram of the cluster head re-selection phase.

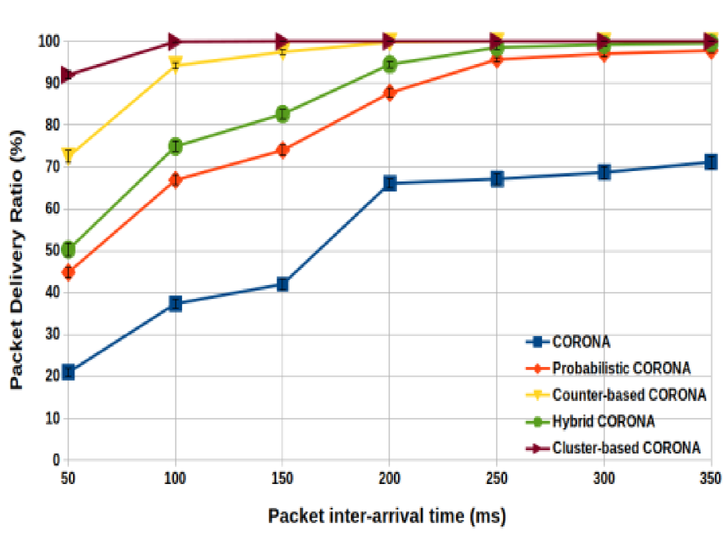
5.3 Comparative Analysis with Existing Approaches

In this section, through extensive simulations on the nano-sim tool **[13]**, we evaluate the routing efficiency of the proposed routing scheme compared to the CORONA routing scheme **[20]** and our previously proposed routing schemes **[64]** presented in **Chapter 3**. We maintain the same assumptions, simulation setup, and key QoS metrics described in the previous chapter. Furthermore, we include the Average End-to-End Delay (AE2ED) metric calculated as follows:

$$AE2ED = \frac{\sum dt_i}{NbrPkt} \qquad (5.3)$$

Where i and N brP kt are the IDs of packets successfully delivered to the destination nodes by all compared routing schemes and the total number of these packets, respectively. While dt_i is the time required to route each packet i from the source to the destination.

5.3.1 Results and Analysis



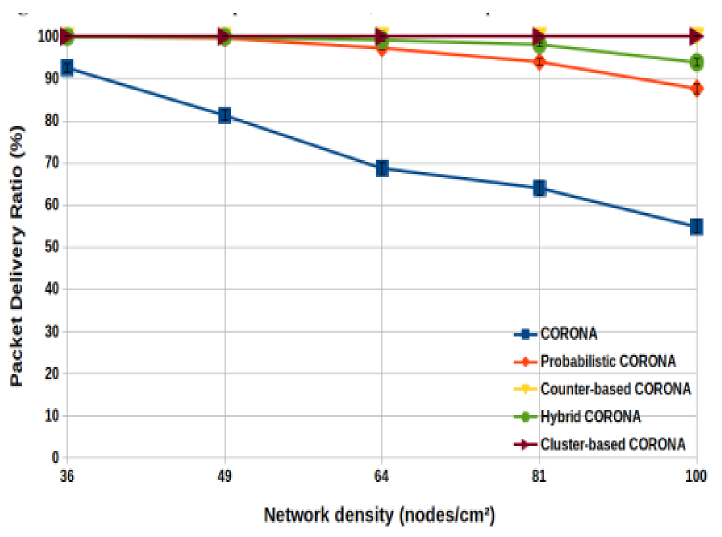


Fig. 5.6: PDR of the compared schemes, versus the packet inter-arrival time.

Fig. 5.7: PDR of the compared schemes, versus the nanonetwork density.

1. Packet Delivery Ratio

The packet delivery ratio is presented over increasing the packet inter-arrival time and the nanonetwork density in Fig. 5.6 and Fig. 5.7, respectively. Fig. 5.6 shows that the time taken between generating two consecutive packets positively affects the PDR of existing routing schemes. The increasing of packet inter-arrival time leads to increasing the packet delivery ratio performance for each scheme. This is expected because the long time between generating two consecutive packets gives nanodevices ample time to harvest energy, numerous nanodevices are available, which increases the probability of successful delivery of the following packet. In contrast, thanks to the used routing strategy, where only a specific set of nanodevices are involved in the forwarding process, the proposed scheme can deal with the shortage of energy resources and offers the highest PDR. Fig. 5.7 shows that the increase of the nanonetwork density does not affect the proposed scheme's packet delivery ratio performance. In contrast, the performances of existing routing schemes, especially CORONA routing scheme, are negatively affected. The higher the nanonetwork density, the more likely collisions and faster packet queue overflow, leading to reduce successfully PDR.

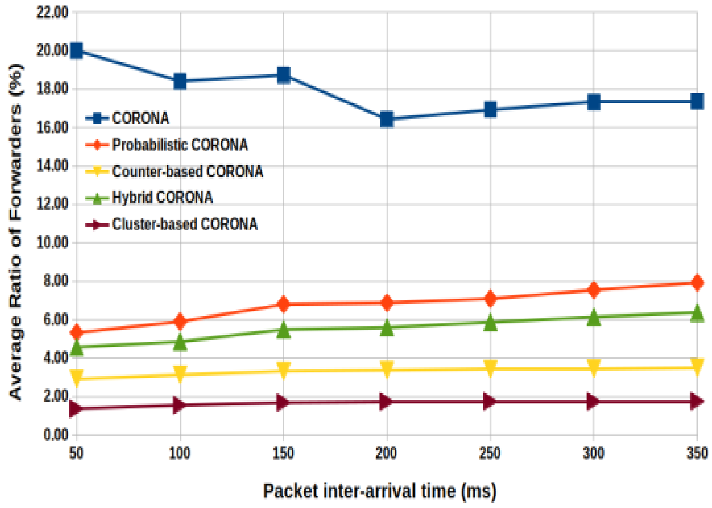


Fig. 5.8: ARF of the compared schemes, versus the packet inter-arrival time.

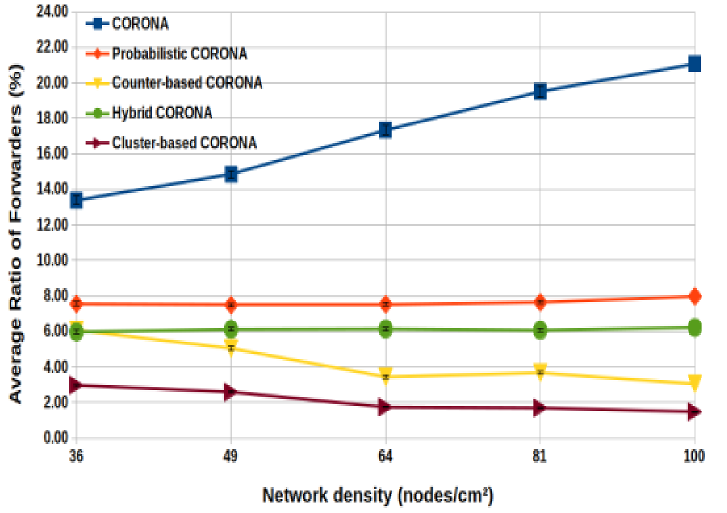


Fig. 5.9: ARF of the compared schemes, versus the nanonetwork density.

2. Average Ratio of Forwarders

We studied the average ratio of forwarders in two cases: *i)* increasing the packet inter-arrival time from 50 to 350 ms and *ii)* varying the nanonetwork density from 36 nodes to 100 nodes per cm^2. Fig. 5.8 shows that the proposed scheme has the best performance and it keeps the same participation rate of nodes in the retransmission process even when the packet inter-arrival time increases. Only CHs and some CMs between communicating nodes are involved. By contrast, CORONA routing scheme shows the worst performance, where the nodes' participation rate in the retransmission process increases as packet inter-arrival time increases. The longer packet inter-arrival time, the more time is available for the nodes to replenish their energy, i.e., a high number of nodes may have enough energy to forward packets, leading to a high number of nodes participating in the retransmission process since the CORONA scheme allows all nodes that have enough energy and located within the communicating nodes to forward. Fig. 5.9 shows that for the proposed scheme, the increase of the nanonetworks density leads to the decrease of the participating nodes in the retransmission process. It is due to the size of clusters which increases and the number of clusters decreases, while only the CHs with a certain set of Cms located between the communicating node-pair are allowed to forward. However, since CORONA routing scheme suffers from the increase of collisions due to the increasing nanonetwork density as shown in Fig. 5.7, thus in high nanonetwork density, CORONA requires high redundant packet transmissions to successfully deliver packets.

3. Average Residual Energy

We studied the average residual energy in the nanonetwork in two cases: i) increasing the packet inter-arrival time from 50 to 350 ms and ii) varying the nanonetwork density from 36 nodes to 100 nodes per cm^2. Fig. 5.10 shows that the residual energy in the whole nanonetwork is proportional to the time between generating two consecutive packets. As a long packet inter-arrival time gives nanodevices more time to harvest energy and vice versa. It can be seen that the proposed scheme keeps the highest residual energy, due to the constrained rate of participating nodes in the retransmission process, as shown in Fig. 5.8. In Fig. 5.11, it can be observed that the proposed scheme offers the best performance and its performance is not affected by the increase of the nanonetworks density. Because regardless of the nanonetwork density, the proposed scheme keeps the same participating rate of nodes in the retransmission process, as shown in Fig. 5.9.

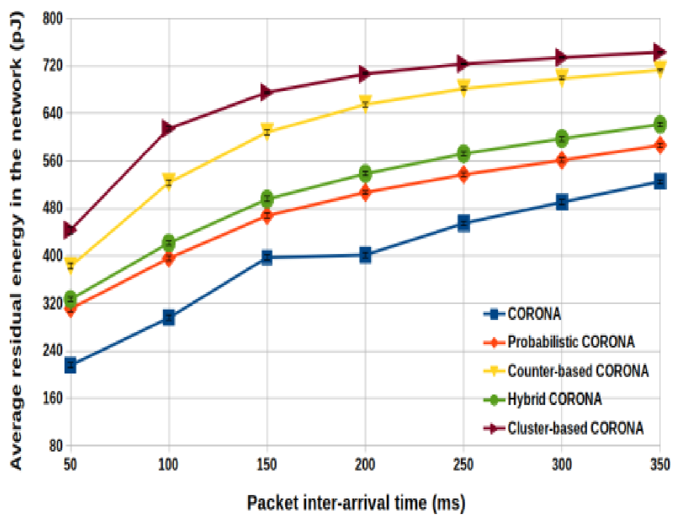


Fig. 5.90: ARE of the compared schemes, versus the packet inter-arrival time.

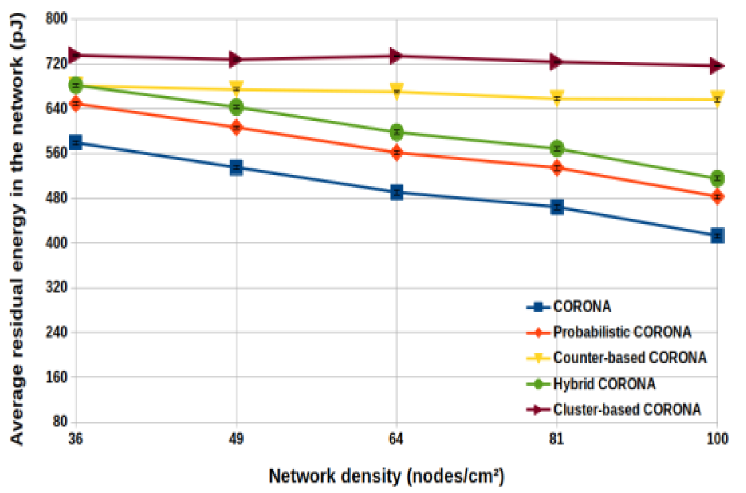


Fig. 5.81: ARE of the compared schemes, versus the nanonetwork density.

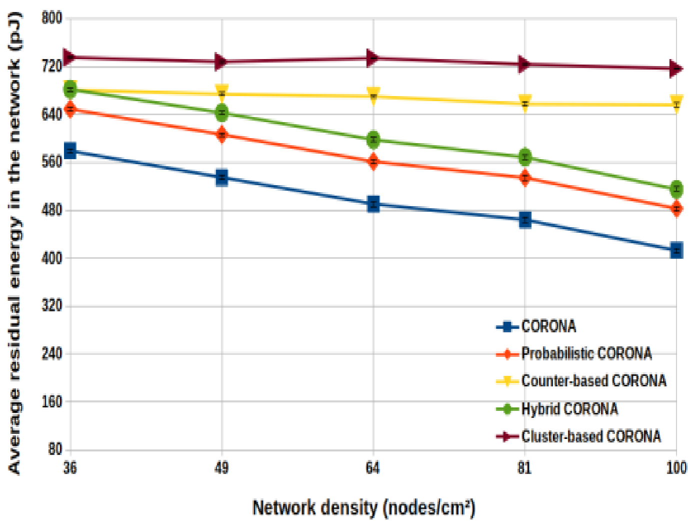


Fig. 5.112: AE2ED of the compared schemes, versus the packet inter-arrival time.

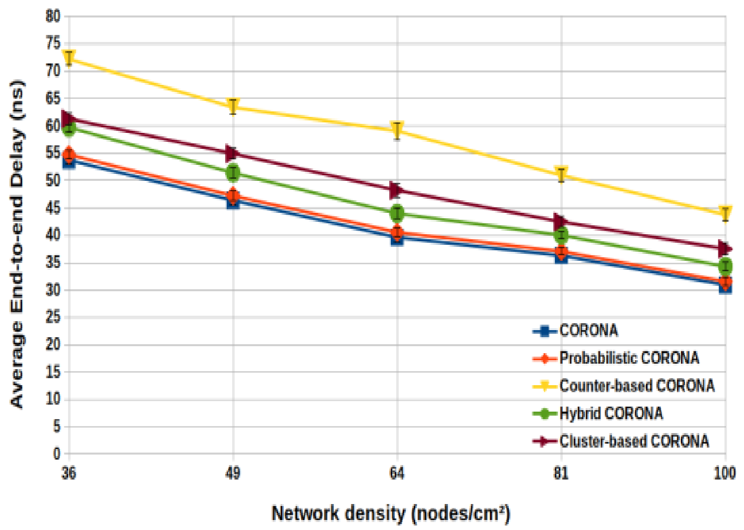


Fig. 5.103: AE2ED of the compared schemes, versus the nanonetwork density.

5. Average End-to-End Delay

We studied the average end-to-end delay of packets that are successfully delivered by all compared schemes in two cases: *i)* increasing the packet inter-arrival time from 50 to 350 ms and *ii)* varying the nanonetwork density from 36 nodes to 100 nodes per cm 2 . Fig. 5.12 shows that for all schemes the increase of packet inter-arrival time leads to a slight increase in this metric. Because as shown in Fig. 5.6, the increase of packet inter-arrival time, allows to successfully deliver new packets. Where the latter have relatively long delays since they are routed through long paths. CORONA routing scheme shows the best performance, due to its redundant path mechanism, where each node within the communicating nodes directly forwards the received packet, thus the shortest path could be among these paths. By contrast, the proposed routing scheme has a longer delay than CORONA's delay, because there is no constraint in terms of delay on the selection of nodes which can forward the packet. Thus, there is no guarantee in this scheme for the packets to be forwarded over the shortest path. Fig. 5.13 shows that when the nanonetwork density increases the average end-to-end delay decreases (for all considered schemes).This makes sense because the increase of nanonetwork density reduces the hop-count distance between communicating nodes, thus limiting the length of paths traversed by each packet from the source node to the destination node.

5.4 Conclusion

In this chapter, we proposed DCCORONA, a distributed cluster-based multi-hop routing scheme designed to address the energy efficiency challenges in dense 2D homogeneous nanonetworks. Unlike conventional cluster-based routing schemes that primarily target data aggregation communication in sparse, heterogeneous networks, DCCORONA introduces a novel architecture tailored for peer-to-peer communication in dense deployments. By organizing nodes into clusters and employing a dynamic Cluster Head (CH) selection mechanism, the proposed scheme effectively regulates data forwarding, minimizing redundant retransmissions and optimizing energy consumption.

The evaluation results demonstrated that DCCORONA significantly improves key performance metrics, including Packet Delivery Ratio (PDR), Average Residual Energy (ARE), Average Ratio of Forwarders (ARF), and Average End-to-End Delay (AE2ED**)**. Specifically, DCCORONA achieved a notable improvement in energy efficiency, maintaining higher residual energy levels compared to flat routing schemes such as CORONA and its derived versions. This enhancement is primarily attributed to the controlled flooding mechanism that limits forwarding nodes to CHs and strategically selected Cluster Members (CMs).

Moreover, the adaptive CH re-election process further contributes to energy conservation by preventing energy-depleted nodes from participating in the routing process, thereby extending the network lifetime. In terms of communication reliability, DCCORONA effectively addresses the die-out problem by employing a counter-based forwarding mechanism among CMs, ensuring robust data delivery even under high-density network conditions.

Despite these gains, the analysis revealed that DCCORONA incurs a slightly higher AE2ED compared to the flat CORONA scheme due to the clustering overhead and the hierarchical forwarding structure. This latency trade-off, however, is mitigated by the substantial reduction in redundant transmissions and the resulting energy savings, making DCCORONA a scalable and sustainable routing solution for dense nanonetworks.

Overall, DCCORONA represents a significant advancement in cluster-based routing for nanonetworks, particularly for applications requiring peer-to-peer communication in dense, homogeneous deployments such as Software-Defined Metamaterials (SDMs), biomedical sensor networks, and industrial monitoring systems. Future work will focus on further optimizing the forwarding decision-making process to reduce latency, potentially incorporating adaptive delay constraints and predictive forwarding strategies based on packet trajectory analysis. Additionally, the integration of cross-layer mechanisms could further enhance the protocol's scalability and communication reliability under varying network densities and dynamic application requirements.

Chapter 6
P2PAFS: Framework for Three Modes of Communication

6.1 Introduction and Problem Definition

Recent advancements in nanomaterials have laid the groundwork for the development of nanoscale components such as processors, memories, and antennas, enabling communication among nanonodes through electromagnetic waves. Among these, graphene-based antennas have emerged as a key enabler, operating in the Terahertz (THz) band to provide extremely high bandwidth while maintaining compact form factors. Despite these advancements, THz communication remains constrained by severe path loss, limiting the communication range of nanonodes to less than one meter. To address these limitations, the Time Spreading On-Off Keying (TS-OOK) modulation scheme was proposed, utilizing short electromagnetic pulses to transmit bits, thereby reducing energy consumption and extending network lifetime.

Building upon these foundational technologies, nanonetworks have enabled the development of complex communication frameworks, forming the backbone of the emerging Internet of NanoThings (IoNT). In particular, dense and homogeneous 2D nanonetworks have gained traction in emerging fields such as Software-Defined Metamaterials (SDMs)**,** where nanonodes coordinate to dynamically alter the electromagnetic properties of a material. Unlike conventional data aggregation communication, SDMs require a broader communication framework to support three distinct modes: peer-to-peer, upward, and downward communication**.**

While the previous chapters addressed peer-to-peer communication through flat and cluster-based routing schemes (e.g., EECORONA and DCCORONA), the present chapter introduces P2PAFS (Peer-to-Peer Addressing and Flooding System) — a comprehensive communication framework that simultaneously supports peer-to-peer, upward, and downward communication in dense nanonetworks. P2PAFS leverages a self-assigning geo-address system to enable localized address management without maintaining routing tables, making it particularly suitable for computationally constrained nanonodes. Additionally, the framework integrates adjusted counter-based and probabilistic flooding mechanisms to mitigate redundant transmissions, thereby optimizing energy consumption and extending network lifetime.

To the best of our knowledge, P2PAFS is the first framework specifically designed to handle all three communication modes — peer-to-peer, upward, and downward — in dense, homogeneous 2D nanonetworks. Existing cluster-based schemes predominantly focus on data aggregation in sparse, heterogeneous networks, consisting of nanonodes, nanorouters, and nanointerfaces. These schemes overlook the unique requirements of emerging application domains, such as Quantum Computing and Wireless Networks In-Package, where supporting the three communication modes is crucial to ensuring efficient and reliable data exchange across densely deployed nanoscale devices.

For instance, in Quantum Computing, nanonetworks are increasingly considered as an enabler of intra-chip communication between qubits and control units. Peer-to-peer communication allows direct data exchange between qubits and quantum registers, **ensuring** ultra-low latency and precise coordination essential for quantum error correction and multi-qubit operations. Furthermore, upward communication is necessary to relay processed data to external control units, while downward communication enables the dissemination of new control directives to qubits.

Similarly, in Wireless Networks In-Package (WiNoP), dense nanonetworks facilitate high-speed, intra-chip communication between multiple chiplets. Peer-to-peer communication in this context is crucial for direct data transfer between chiplets, reducing latency and bus congestion. Upward and downward communication modes are also required to coordinate data exchange between internal processing units and external control entities, ensuring system integrity in multi-core architectures.

Therefore, the proposed P2PAFS framework is designed to address these diverse communication requirements by implementing a unified architecture that supports peer-to-peer interactions for localized data exchange, upward communication for data dissemination to external entities, and downward communication for directive dissemination from external controllers.

The present chapter is structured as follows: **Section 6.2** details the operational framework of P2PAFS, explaining the implementation of the addressing system and the communication mechanisms for peer-to-peer, upward, and downward modes. **Section 6.3** provides a comprehensive performance analysis, focusing on key QoS metrics, including Packet Delivery Ratio (PDR), Average Residual Energy (ARE), Average Ratio of Forwarders (ARF), and Average End-to-End Delay (AE2ED). Finally, **Section 6.4** concludes the chapter, summarizing key findings and suggesting areas for further optimization.

6.2 Peer-to-Peer, Upward, Downward Communication Framework

Firstly, **Section 6.2.1** presents the self-assigning address and classification system, where each nanodevice independently determines its non-unique geo-address based on its spatial coordinates and evaluates its role as a forwarder for the subsequent communication phase. Then, **Section 6.2.2**, **Section 6.2.3**, and **Section 6.2.4** detail the operating processes of peer-to-peer, upward, and downward communications, respectively, outlining the mechanisms employed to optimize data exchange in dense nanonetworks through counter-based and probabilistic flooding techniques.

6.2.1 Setting-up Geo-addresses and Self-classification

The proposed self-assigning geo-address and classification system that extends the DEROUS setup phase [25] is detailed as follows:

1. Firstly, the proposed system assume that the nanodevices are uniformly distributed in a circular area and around the centered nanodevice, namely BEACON-node. However, unlike DEROUS, the proposed system could also treat with rectangular areas as will illustrate later.

2. Using the normal-power transmission, the BEACON-node broadcasts the first setup packet containing the corresponding SETUP flag and the hop-count field, N HOPS is set to 1 (see Fig. 6.1a).

Flag	Meaning	Packet structure		
		Header		Payload
000	First setup packet using NORMAL_POWER	SETUP (3-bit flag)		N_HOPS (int)
001	Second setup packet using LOW_POWER	SETUP (3-bit flag)		L_HOPS (int)
010	Third setup packet contains the current direction	SETUP (3-bit flag)		DIRECTION $\lceil \log_2(360) \rceil$ bits
011	HELLo packet	SETUP (3-bit flag)		N_HOPS (int)
11	Data packet	SETUP (2-bit flag)	Pkt_ID (8 bits)	DATA (var)
		Source address (int, int, $\lceil \log_2(360) \rceil$)	Destination address (int, int, $\lceil \log_2(360) \rceil$)	

(a) Used packets in the proposed schemes

Nanodevice state	DIF_NORMAL (1 bit)	DIF_LOW (1 bit)	HIGHER-LEVEL (1 bit)
Nanodevice geo-address	HOPS_N (int)	HOPS_L (int)	DIRECTION $\lceil \log_2(360) \rceil$ bits

(b) Required nanodevice memory

Fig. 6.1: Requirements in terms of packet headers and nanodevice memory.

3. Upon receiving the first setup packet, each nanodevice sets its memory field HOPS N (see Fig. 6.1b) to the minimum N HOPS value over incoming packets, and then it broadcasts the packet using the normal-power transmission after incrementing the N HOPS value of this packet.
4. If the receiving nanodevice is ready, in other words, if this nanodevice is not failed and has enough energy to forward some incoming packets during the next communication phase, it starts to record packet reception statistics to deduce whether it should serve as a forwarder or user. Otherwise, it directly classifies itself as user, as illustrated in Fig. 6.2. The classification result is saved at its memory field DIF-NORMAL (see Fig. 6.1b).
5. Using the simplified variant of Misra-Gries algorithm [25], with trivial integer operations, each nanodevice can determine the most frequent item in its sequence of packet reception statistics (i.e., successful, erroneous or duplicating packet receptions), after only three packet receptions.
6. If the successful packet reception is the most frequent item, the given nanodevice classifies itself as forwarder. If not the case, the given nanodevice will serve as user (see Fig. 6.2).
7. After a safe timeout to avoid interfering the first setup packet, the BEACON-node adjusts its power transmission to the low-power, and then broadcasts the second setup packet.

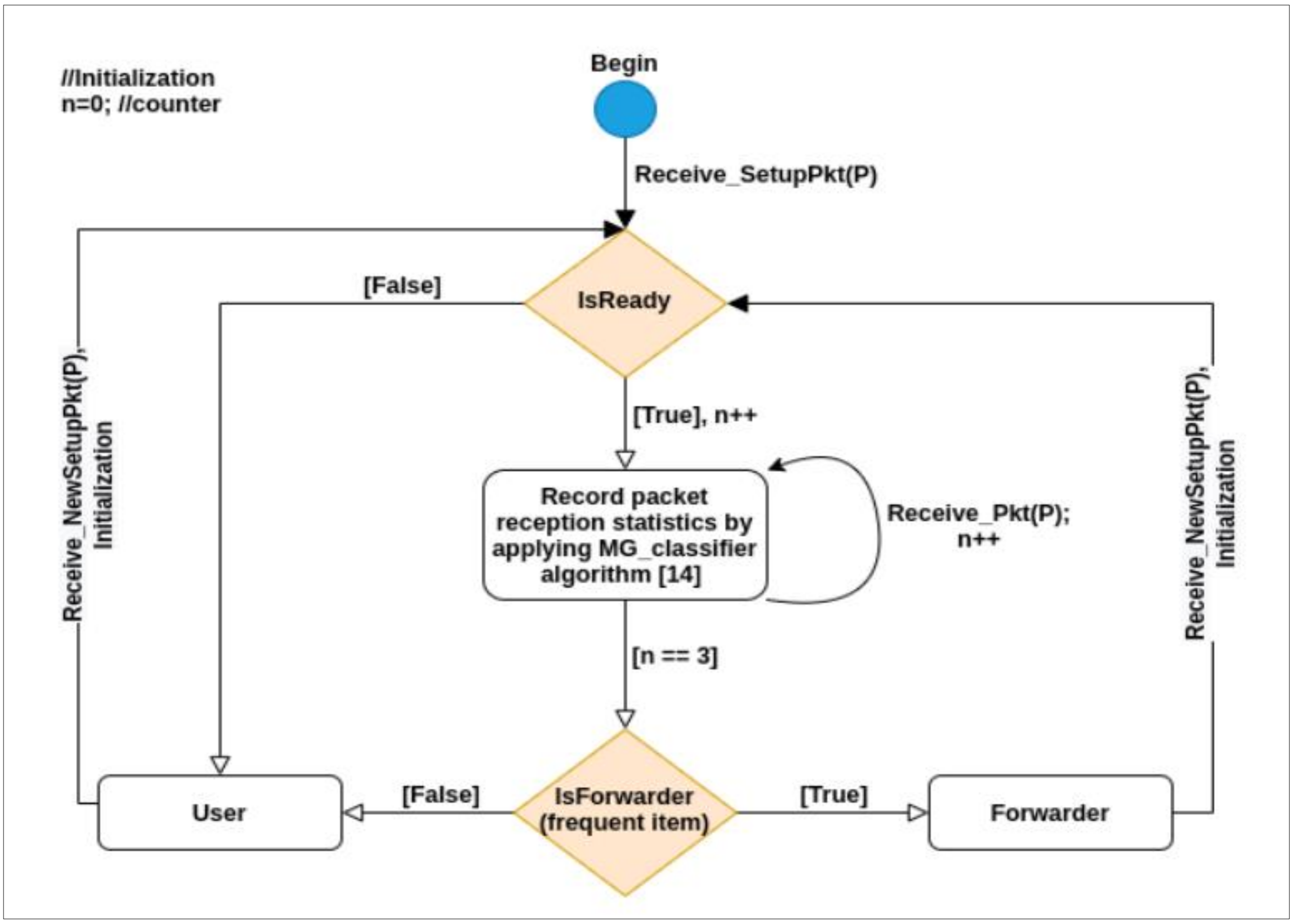


Fig. 6.2: Block scheme of the algorithm executed at all nanodevices during the self-assigning address and classification phase.

8. Symmetrically, the nanodevices will proceed with this packet in the same way as for the first one. However, at this time, the self-classification is reversed than before; the nanodevices that are susceptible to the high duplicating and erroneous packet receptions will act as forwarders, while the rest having a good reception statistics will act as users. On the one hand, this decision will accelerate and achieve high packet delivery since when the forwarders retransmit a packet, simultaneously, a high number of nanodevices with a good reception quality receive this packet. On the other hand, the number of nanodevices classified as forwarders is reduced by almost 15%.

9. Finally, instead of transmitting the third setup packet in the whole BEACON-node transmission range, as such with the previous packets, in this time, we will exploit the beamwidth and steerable antenna of the BEACON-node to divide the circular area into many sectors. The narrow the beamwidth, the narrow sectors are generated, reducing the number of nodes located in the same area (the nodes with the same geo-address). Hence, achieving better performance during the routing process as the flood area became more restricted.

10. The BEACON-node rotates its antenna direction in discrete steps as follows:

$$\begin{gathered} initial\ direction = 0^\circ \\ next\ direction = current\ direction + antenna\ beamwidth \\ final\ direction = 360^\circ \end{gathered} \tag{6.1}$$

11. In each step, the BEACON-node emits the third setup packet containing the current direction in degree. Only nanodevices located on BEACON-node's antenna beamwidth can
12. receive this packet.
13. After achieving a whole antenna rotating, each nanodevice has been set its memory field DIRECTION to the received packet's DIRECTION field.

At the end, each nanodevice knows its not unique address that is composed of three attributes (HOPS N, HOPS L, DIRECTION) and its classification according to both normal-power and low-power transmissions (DIF-NORMAL, DIF-LOW). Noting, the BEACON-node periodically repeats this process to support the change in the nanonetwork topology (new nanodevices, failing nanodevices, insufficient energy and resources).

6.2.2 Peer-to-Peer Addressing and Flooding System

In the previous phase, the use of normal-power transmission has allowed building multi-levels around the BEACON-node corresponding to the hop-count distance between each nanodevice and the BEACON-node (HOPS N). For each level, the forwarders form a circular pattern around the users of this level, as presented in Fig. 6.3a. While, the classified forwarders when using the low-power transmission form radial lines connecting the nanodevices of adjacent levels, as presented in Fig. 6.3b. Based on these peculiarities and the angle-aware position relative to the BEACON-node, the proposed approach routes the data packets along radius and arc paths around the BEACON-node, as shown in Fig. 6.4. Moreover, the proposed scheme jointly applies adjusted counter-based and probabilistic flooding techniques on the constructed routing paths to reduce efficiently the number of redundant packet retransmissions. As summarized in Fig. 6.5, the proposed hybrid routing scheme involves the following steps:

1. Upon receiving a packet pkt, each forwarder checks whether this packet has never been treated, to avoid route loops. A treated packet means that this packet has been already forwarded or ignored from this nanodevice.
2. Since the forwarder x has never treated this packet, it checks if this the first reception. If not the case, a packet counter redundancy is incremented. This counter aims to guarantee that this packet is forwarded at least a given number of times R by the neighboring forwarders.
3. If this is the first reception of a packet pkt, the forwarder x decides whether to forwards it or not using the following integer-based criterion:

$$\boxed{\begin{array}{c} (pkt.S.HOPS\_N\ -1\ =\ x.HOPS\_N\ \&\&\ x.DIF\_NORMAL)\ \| \\ (pkt.D.HOPS\_N\ -1\ =\ x.HOPS\_N\ \&\&\ x.DIF\_NORMAL)\ \| \\ (x.HOPS\_L \in [pkt.S.HOPS\_L;\ pkt.D.HOPS\_L]\ \&\&\ x.DIF\_LOW) \end{array}} \tag{6.2}$$

The first two clauses of criterion (6.2) relate to the classified forwarders when using normal-power transmission. Only the forwarders located at the direct lower level of source (S) or destination (D) are selected to participate in the forwarding process. On the one hand, this choice reduces the forwarding operations of the forwarders located at the higher level, allowing them to save their energy for use in data dissemination between the nanonetwork and the external world as will illustrate later. On the other hand, unlike DEROUS routing process, relying on the forwarders located at the direct lower level of the communicating node-pair allows the proposed scheme to relay packets to nanodevices with no forwarders in their level, as illustrated in Fig. 6.4b. While the third clause relates to the classified forwarders when using low-power transmission. Only the forwarders located between the communicating node-pair are selected to participate in the forwarding process.

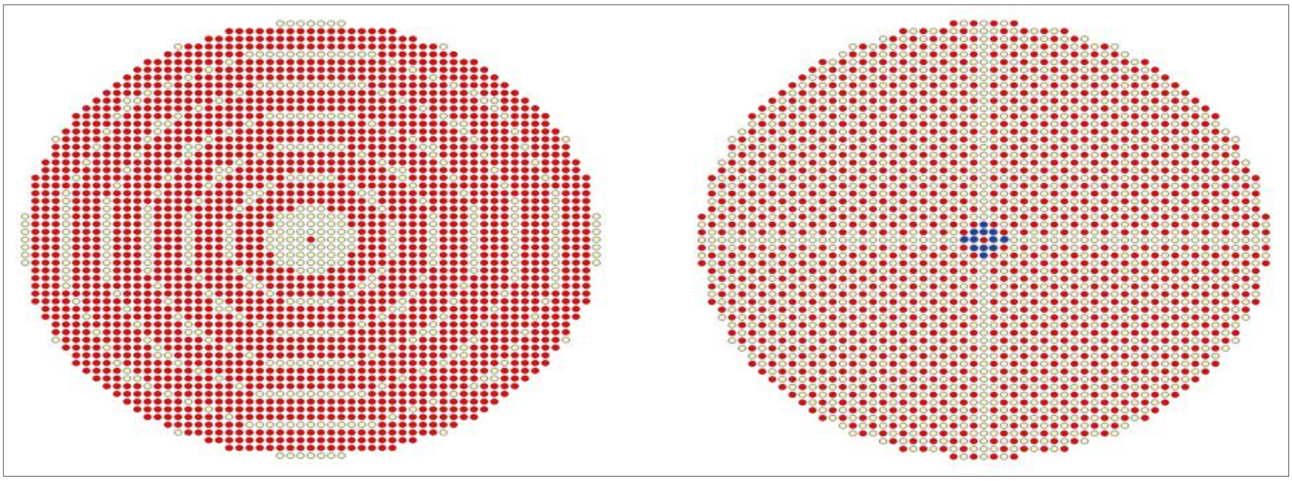
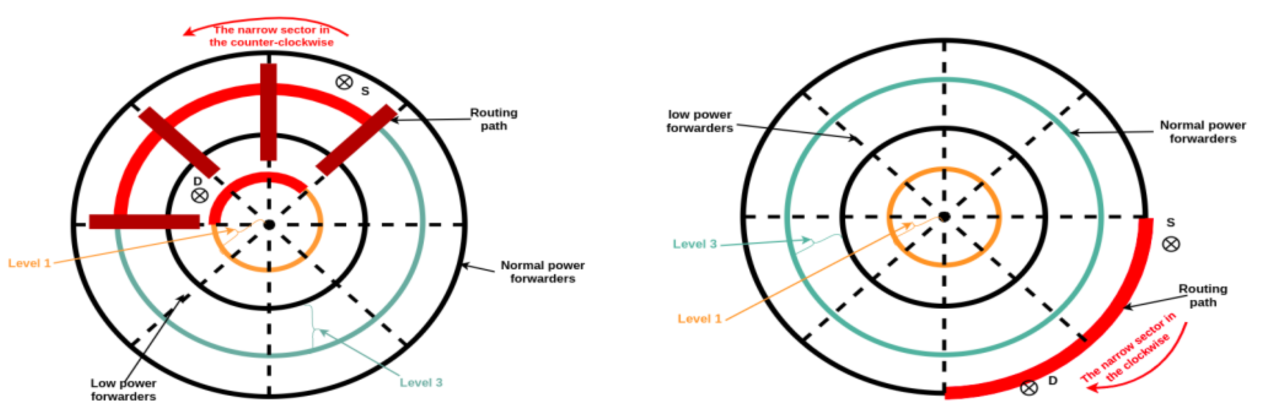


Fig. 6.3: Well-defined patterns that obtained during simulations.

4. To further reduce the number of forwarders selected in the previous step, the following criterion allows only the forwarders located in the narrow sector arcs between the communicating node-pair to forward. As shown in Fig. 6.4, the narrow sector could be in the counter-clockwise or clockwise relative to the source, according to the first or second clause of criterion (6.3), respectively.



(a) Case 1: the source and destination nodes are located at different levels

(b) Case 2: the source and destination nodes are located at the same level

Fig. 6.4: Illustration of the existing routing cases of P2PAFS scheme. The positions of the source (S) and destination (D) are interchangeable.

$$(|pkt.S.DIRECTION - pkt.D.DIRECTION| \leq 180 \;\; \&\& \;\; x.DIRECTION[\,pkt.S.DIRECTION,\; pkt.D.DIRECTION])$$
$$\|$$
$$(|pkt.S.DIRECTION - pkt.D.DIRECTION| > 180 \;\; \&\& \;\; x.DIRECTION]\,pkt.S.DIRECTION,\; pkt.D.DIRECTION[) \quad (6.3)$$

5. Since the proposed scheme belongs to the flood-based scheme class, which suffers from the well-known broadcast storm problem [23], a probabilistic flooding technique is used to avoid this problem. The selected forwarders in the previous step forward a packet pkt with the following forwarding energy-based probability:

$$P1 <= min\left(\frac{1}{2},\; \frac{E_{level} - E_{off} - E_{pkt-Tx}}{E_{max}}\right) \quad (6.4)$$

where E_{level} is the current energy level of the given forwarder, E_{off} is the required energy level to power its hardware, E_{pktTx} is the required energy level to transmit a packet and E_{max} is the maximum energy level. The forwarding probability *P1* addresses a trade-off between energy consumption and latency, where the forwarders with a higher energy level have a high chance to forward incoming packets in order to accelerate the communication. However, in the best case, the forwarders retransmit this packet with the forwarding probability of 1/2 since the forwarders form radius lines and circular patterns, thus each one has at least two forwarders in its neighboring.

6. To avoid the die out problem **[1]**, which may occur due to the forwarding probability *P1*. The forwarder that does not retransmit a packet pkt delays this packet until the expiration of a random timeout RAD to try to retransmit it again, with a density-based forwarding probability *P2*. Otherwise, it ignores this packet upon receiving the intended redundancy copies R.

$$P2 <= \frac{i}{\frac{n}{2}} \quad (6.5)$$

where i is the number of iterations used to adjust the flooding and n is the number of neighboring forwarders, while (n/2) is the assumed number of neighboring forwarders that did not forwarder a packet pkt due to **P2**. It can be simply determined n after the end of the self-assigning addresses and classification phase by exchanging HELLO packets between forwarders. At each iteration, the chances of forwarding increase with 1/(n/2), because on average (i−1)/(n/2) of forwarders retransmit the packet in the previous iterations.

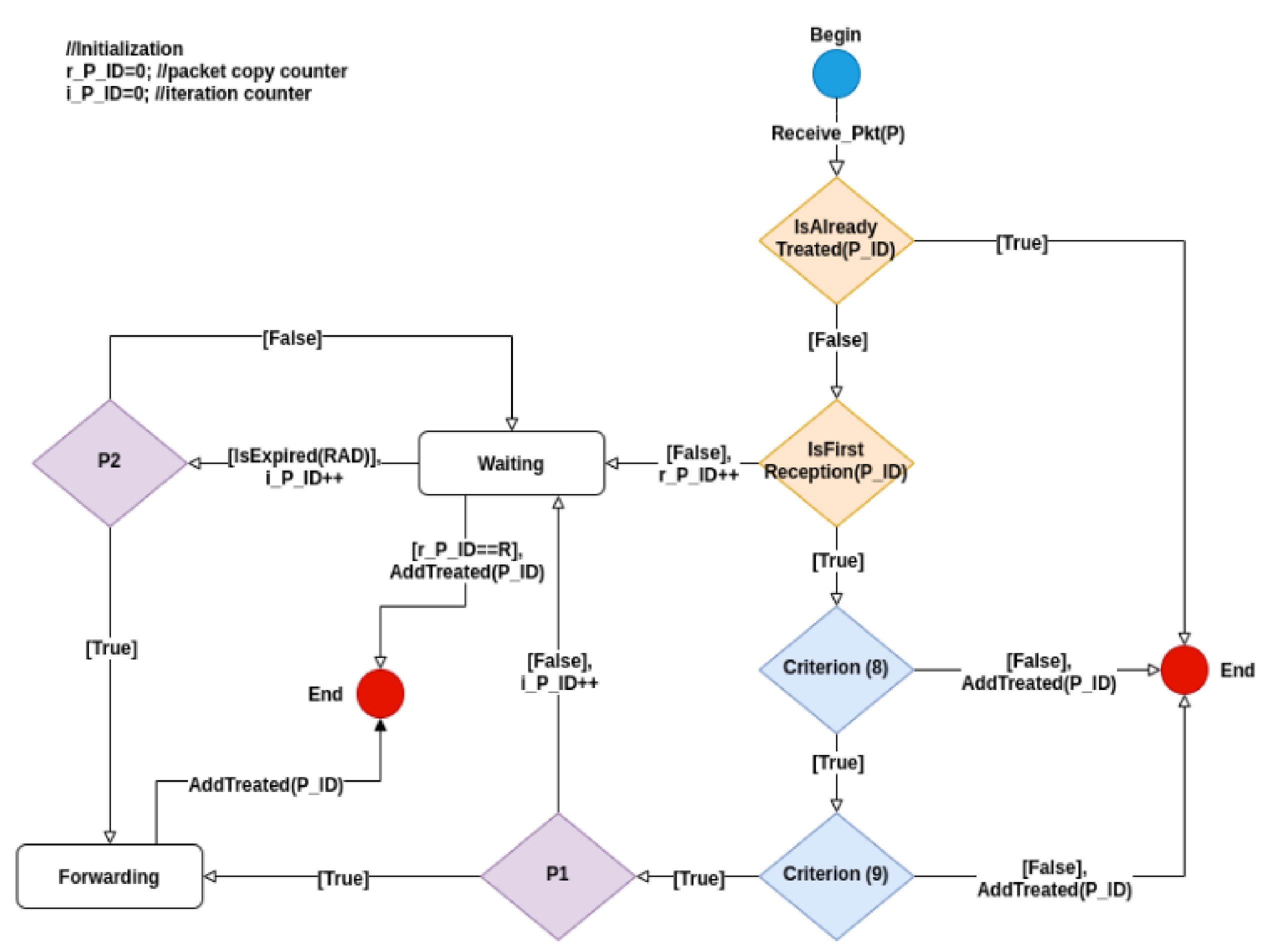


Fig. 6.5: Block scheme of the proposed routing scheme executed by the classified forwarders.

7. Each forwarder randomly chooses RAD inside the dynamically adjusted time window t, that aims to avoid wasting time at the cost of communication latency, given by:

$$t = \alpha * (n/2 - i) * T \tag{6.6}$$

where n is the number of neighboring forwarders of a given forwarder, i is the number of iterations and α is a parameter that allows adapting to the peculiarities of the used modulation technique TS-OOK, which permits the interleaved of packets at the receiving nanodevice. Where α = 1 means there is no interleaving, such as in the traditional networks. Henceforth, α = 1/C, in order to get a trade-off between the delay and occupied memory, where C is the number of interleaved packets that a nanodevice can concurrently track and process. While, T is the time required to receive a packet, to decode it and to decide to forward it, given by:

$$T = N_{bits} * T_p + (N_{bits} - 1) * T_s + T_l + T_d \tag{6.7}$$

where N bits is the packet size in bits, T_p is the time to transmit an EM pulse, T_s is the time between transmitting two consecutive bits, T_d is the time required to decode and decide to forward a packet and T l = c/d is the propagation time of the last bit, where c and d are the speed of light, and the communication range, respectively.

6.2.2 DIF-based Data-centric Schemes

In this section, we will present the adaptation of the proposed peer-to-peer routing scheme to take charge of the bidirectional flood-based communications between the nanonetwork and the external entity. Firstly, Section 6.2.2.1 presents the proposed scheme that considers the routing of data from nanodevices towards the external entity (upward data). We refer to this scheme as DIF-based upward scheme. While Section 6.2.2.2 presents the proposed data dissemination scheme that deals with the dissemination of data coming from the external entity towards all nanodevices (downward data). We refer to this scheme as DIF-based downward scheme.

6.2.2.1 DIF-based Upward Scheme

Since the external entity has no fixed position, the upward data must be disseminated to all sides, with high coverage to guarantee that data ultimately reach the external entity. Moreover, such communications are processed at run-time, therefore a low communication latency is demanded. The DIF-based upward scheme aims to both maintain high coverage and low delivery time, as well as reduce redundant retransmissions. Hence, the DIF-based upward scheme customizes the routing process of P2PAFS presented in Fig. 6.2 to route data along radius paths (straight paths), by changing the criterions (6.2) and (6.3) with the following one:

$$\boxed{\begin{array}{c}(pkt.S.HOPS\_L < x.HOPS\_L \;\&\&\; x.DIF\_LOW) \;\| \\ (x.HIGHER\_LEVEL \;\&\&\; x.DIF\_NORMAL)\end{array}} \quad (6.8)$$

The first clause relates to the classified forwarders when using low-power transmission. Only forwarders farther away than the source node from the BEACON-node are allowed to participate in the forwarding process. While the second clause relates to the classified forwarders when using normal-power transmission. Only forwarders located at the higher level are selected to participate in the forwarding process, in order to further guarantee that the upward packets reach all sides of the nanonetwork. Noting, when exchanging HELLO packets between forwarders after the end of the self-assigning addresses and classification phase, each forwarder has set its memory field HIGHER LEVEL to 1, if it has never received HELLO packet contains N HOPS greater than its own (see Fig. 6.1a).

6.2.2.1 DIF-based Downward Scheme

Similarly, the downward data must be disseminated over the entire nanonetwork with a low delivery time. Accordingly, DIF-based downward scheme route downward packets in the same manner as DIF-based upward scheme. However, all forwarders that classified when using low-power transmission are selected to participate in the forwarding process, because in this time, the source node is the external entity, and all nanodevices must receive the downward data.

6.3 Performance Evaluation

In this section, through extensive simulations on the nano-sim [13], we simulate the required communication modes of SDM applications, (i.e., peer-to-peer and data-centric) to evaluate the performance of the proposed schemes versus related approaches. Firstly, we describe the evaluating metrics and the different performance scenarios that have been considered for the peer-to-peer and data-centric modes in Section 6.3.1 and Section 6.3.2, respectively. Then, we present the simulation setup and assumptions in Section 6.3.3. Finally, in Section 6.3.4, we discuss the obtained results.

6.3.1. Evaluating Metrics and Performance Scenarios for Peer-to-Peer Mode

To see the behavior of the P2PAFS scheme, we consider the same evaluation metrics used in [27, 28], which are considered as rigorous metrics for evaluating the resource-efficiency of nanonetworks [9, 12, 21]: Packet Delivery Ratio (PDR), Average Ratio of Forwarders (ARF), Average Residual Energy (ARE) and Average End-to-End Delay (AE2ED). These metrics are logged against: I) increasing the nanonetwork density from 36 nodes to 100 nodes per cm 2 and ii) increasing the packet inter-arrival time from 50 to 350 ms. In each simulation, a series of 100 operation cycles occur, in each one, the communicating node-pair is selected randomly. Two versions of the P2PAFS scheme using two different antenna beamwidths (30◦ and 6◦) are considered in order to show the impact on the routing performance when using narrow or width antenna beamwidth by the BEACON-node in the setup phase.

6.3.2. Evaluating Metrics and Performance Scenario for Data-centric Mode

In each simulation, a series of 100 operation cycles take place, in each one, the external entity is positioned randomly on the boundaries of the nanonetwork. Where in downward data, the external entity broadcasts a data packet to all the nanodevices of the network. While, in upward data, the source node is selected randomly before emitting a data packet to the external entity. Over increasing the nanonetwork density from 36 nodes to 100 nodes per cm 2 , the following evaluating metrics are logged: i) the reachability: in downward data, we define the reachability as the ratio of packet successfully received by the external entity. While in upward data, we define the reachability as the ratio of nodes successfully received a packet from the external entity, ii) the cost: in both downward and upward data, we define the cost as the ratio of nodes that participate in the forwarding process and iii) the communication latency: in downward data, we define the communication latency as the average time taken for a packet to reach all the nodes in the network. While, in upward data, we define the communication latency as the average time taken for a packet generated from a nanodevice of the network to reach the external entity. Moreover, for both peer-to-peer and data-centric modes, we compute the Erroneous Packet Receptions Rate (EPRR), as follows:

$$EPRR = \frac{GlobalErrPkt}{SuccComm} \tag{6.9}$$

where GlobalErrP kt is the number of erroneous packet receptions in the whole network per simulation due to i) collisions, ii) overflowing of the number of interleaved packets that a nanodevice can concurrently process and overflowing of the nanodevice queue and iii) low received signal strength due to the lossy conditions of the THz band. While, SuccComm represents the PDR and the reachability for the peer-to-peer and data-centric modes, respectively.

Table 6.1: Default simulation settings and the corresponding settings for each scenario.

Parameter	Value
Frequency $[THz]$	0.1
Pulse duration $[fs]$	100
β: TS-OOK time spread ratio	100
SNR $[dBm]$	-100
Communicating range $[cm]$	1
Nanonetwork size	1500
Packet payload size $[bits]$	100
Node queue length	20
t_{cycle}: harvesting cycle time $[ms]$	20
C: number of interleaved packets	5
R: redundancy parameter	1
Scenario 1: varying packet inter-arrival time	
Packet inter-arrival time $[ms]$	50, 100, 150, 200, 250, 300, 350
λ: spacing $[cm]$	0.125
Scenario 2: varying nanonetwork density	
Packet inter-arrival time $[ms]$	200
λ: spacing $[cm]$	0.166, 0.142, 0.125, 0.111, 0.1

6.3.3. Simulation Setup and Assumptions

Since the present study targets applications in SDMs, we simulate the embedded nanocontrollers by 1500 energy harvesting nodes deployed within 2D circular uniform regular grid layouts. The grid spacing λ varies according to the corresponding performance scenario. Further, a random layout is considered to study the sensitivity of the proposed scheme under rigorous conditions. The energy is harvested from air-vibrations, with the vibration frequency set to 50 Hz [41], which can be accurately modeled as described in Section 3.2. The maximum storage capacity of a node is set to 800 pJ. Identically, the BEACON-node located in the center of the deployment area is resource-constrained, but it differs from the other nodes by its directional antenna. During the setup phase, all nodes are assumed to transmit packets in two modes: i) low-communicating range and ii) normal-communicating range. The low-communicating range is carefully selected to include the twelve immediate neighbors of a given node. The blue nodes in Fig. 6.3b represent the twelve immediate neighbors of the BEACON-node. While the normal-communicating range is two times bigger, in order to have several levels. Any change in the communicating ranges leads to a change in the well-defined pattern of forwarders [14, 15]. While, during the communication phase, to evaluate the performances of the proposed schemes compared to related works under the same conditions, the communication range of all nodes is set to 1 cm. Table 2 shows the summary of the default simulation settings and the corresponding settings for each scenario. It worth noting that each value in Figures 8-25 represents the average value of 50 values obtained by repeating simulation run 50 times. The error bars indicate the 95% confidence intervals which indicates that the obtained results are credible.

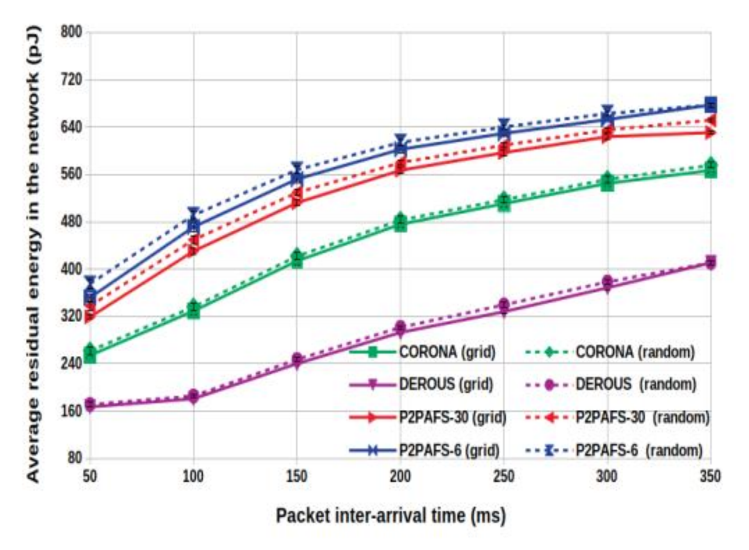


Fig. 6.6: ARE of the compared schemes, versus the packet inter-arrival time.

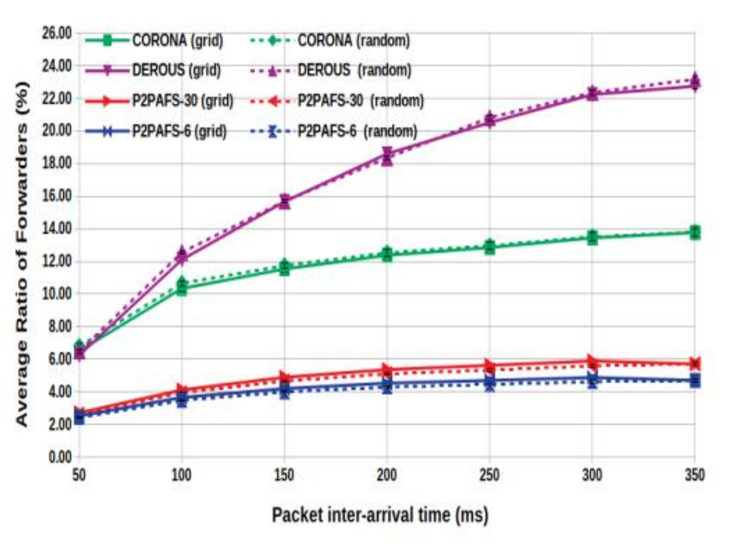


Fig. 6.7: ARF of the compared schemes, versus the packet inter-arrival time.

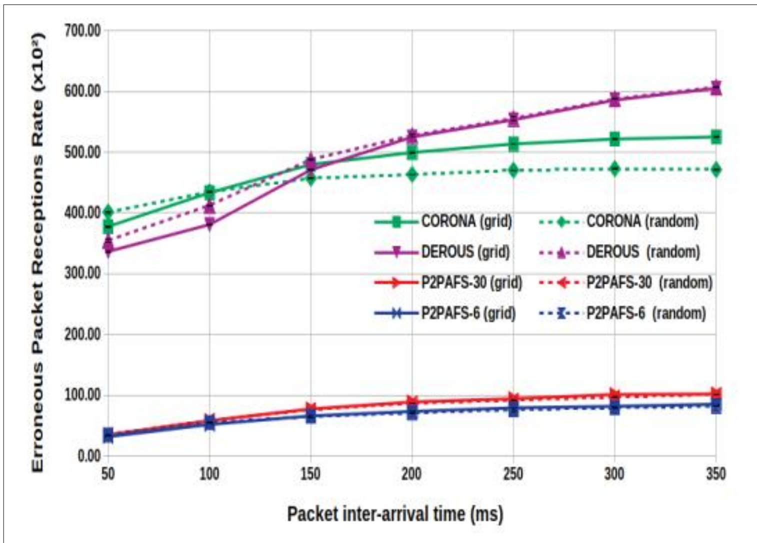


Fig. 6.8: EPRR of the compared schemes, versus the packet inter-arrival time.

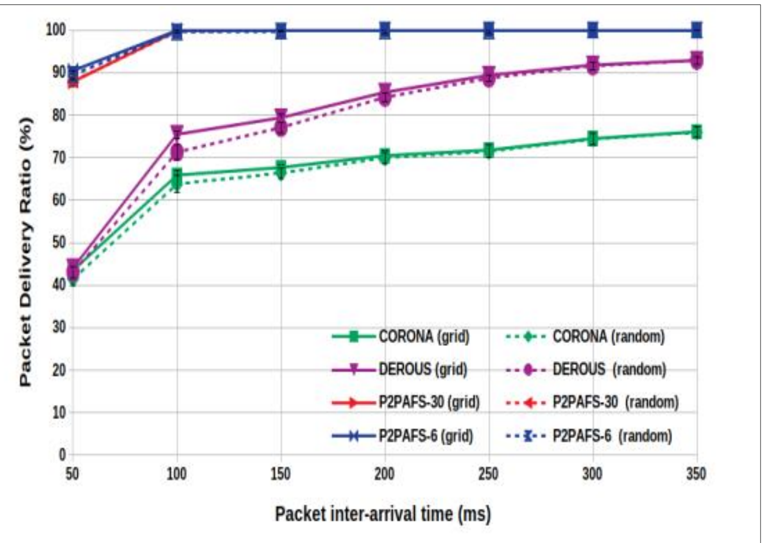


Fig. 6.9: PDR of the compared schemes, versus the packet inter-arrival time.

6.3.4 Results and Analysis

6.3.4.1 Peer-to-Peer Scenario: varying packet inter-arrival time

Generally, increasing the packet inter-arrival time positively affects the average residual energy in the whole network, as shown in Fig. 6.6. This is expected because the long time between generating two consecutive packets gives nanodevices ample time to harvest more energy. Due to the multi-path nature of the compared schemes, the higher residual energy, the more likely available paths appear between the communicating node-pairs, leading to a high number of nanodevices participating in the forwarding process, as illustrated in Fig. 6.7. However, thanks to the restricted and selective selection of forwarders, the proposed scheme shows the best performance in terms of ARF. Accordingly, since the P2PAFS-6 is more restricted than P2PAFS-30, it requires fewer number of forwarders. Fig. 6.8 presents the sufferance of the compared schemes from the broadcast storm problem since they are flood-based schemes. However, the proposed scheme suffers less, because it deals efficiently with this problem by reducing the number of redundant retransmissions and adopting the counter-based mechanism, which reduces the overflow of nanodevice queue and collisions. Therefore, the proposed scheme offers a rational energy consumption and shows the best performance, as presented in Fig. 6.6. Moreover, in Fig. 6.9, it can be seen that the proposed scheme deals efficiently with the shortage of energy resources and offers the highest PDR, while DEROUS scheme shows better performance than CORONA, but at the cost of residual energy. Fig. 6.10 presents the average end-to-end delay of packets that are successfully delivered by all compared schemes. In grid layout, the performance of the proposed scheme is not affected by the increase of the packet inter-arrival time, while the performance of existing schemes is negatively affected. Because as shown in Fig. 6.9, the increase of packet inter-arrival time, allows existing schemes to successfully deliver new packets. Where the latter have relatively long delays since they are routed through long paths. Overall, in random layout, the performance of any scheme is getting better with the increase of the packet inter-arrival time, approaching its performance in grid layout. Because, the higher residual energy, the more likely available short paths appear, which reduces the communication latency.

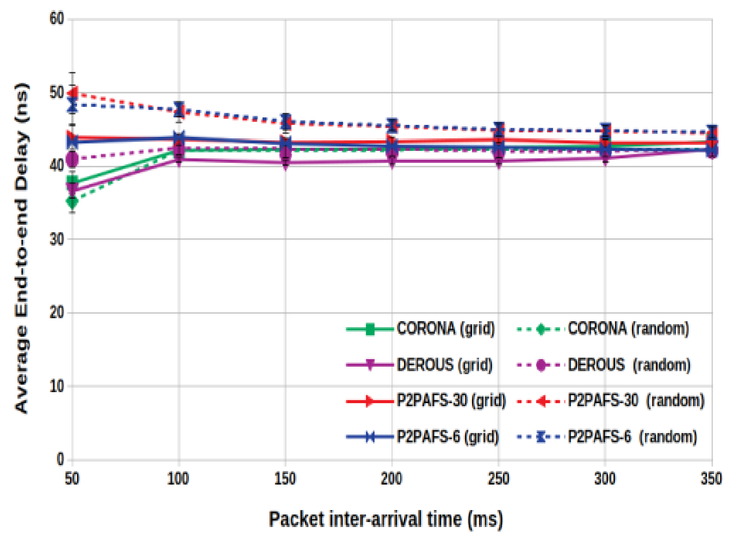


Fig. 6.6: AE2ED of the compared schemes, versus the packet inter-arrival time.

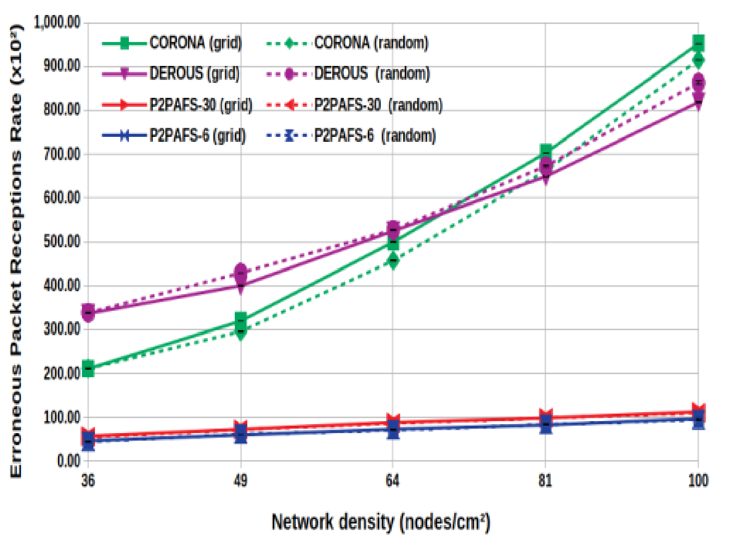
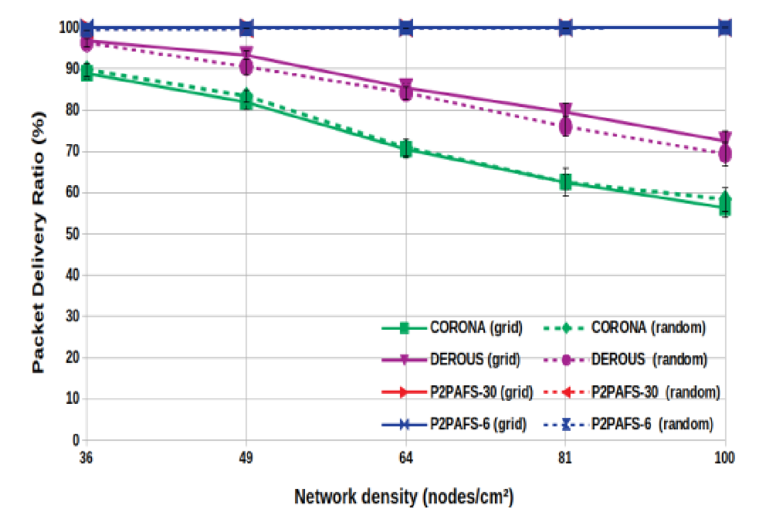


Fig. 6.7: EPRR of the compared schemes, versus the nanonetwork density.

6.3.4.2. Peer-to-Peer Scenario: varying nanonetwork density

Regardless of the scheme, as shown in Fig. 6.11, the increase of nanonetwork density leads to the increase of erroneous packet receptions rate. The larger the neighboring nanodevices, the more likely simultaneous forwarding, thus, the more likely occurring of collisions and nanodevice queue overflow. In contrast to related schemes, the proposed scheme shows a slight increase of erroneous packet receptions rate over the increase of nanonetwork density, leading to maintain its communication reliability, as shown in Fig. 14. In Fig. 15, it can be seen that the proposed scheme offers the best performance in terms of ARF, requiring a low ratio of forwarders participating in the retransmission process. Since the proposed scheme and DEROUS are DIF-based schemes, the increase of nanonetwork density leads to the decrease of the number of forwarding process. Because, more likely erroneous packet reception occur at a set of the classified forwarders, thus, the latter ignore the packet.



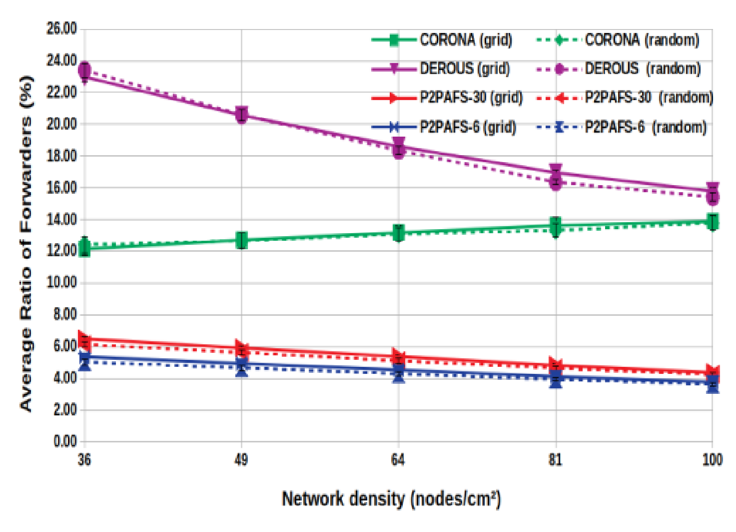
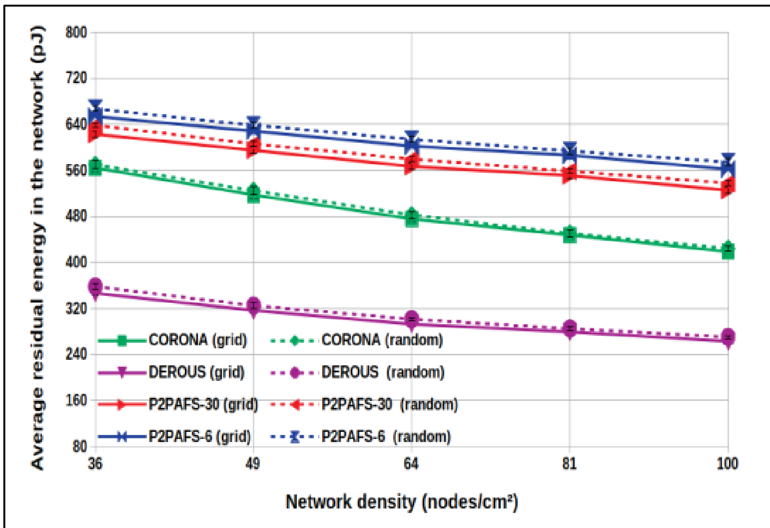


Fig. 6.112 : PDR of the compared schemes, versus the nanonetwork density.

Fig. 6.9ARE of the compared schemes, versus the nanonetwork density.



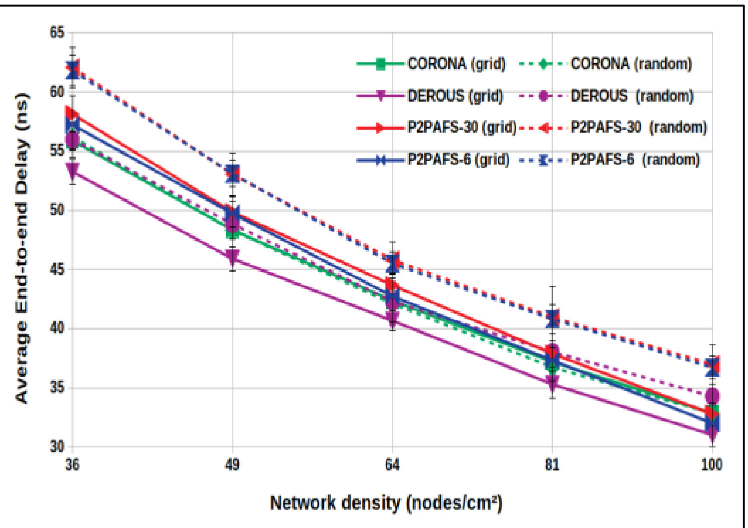
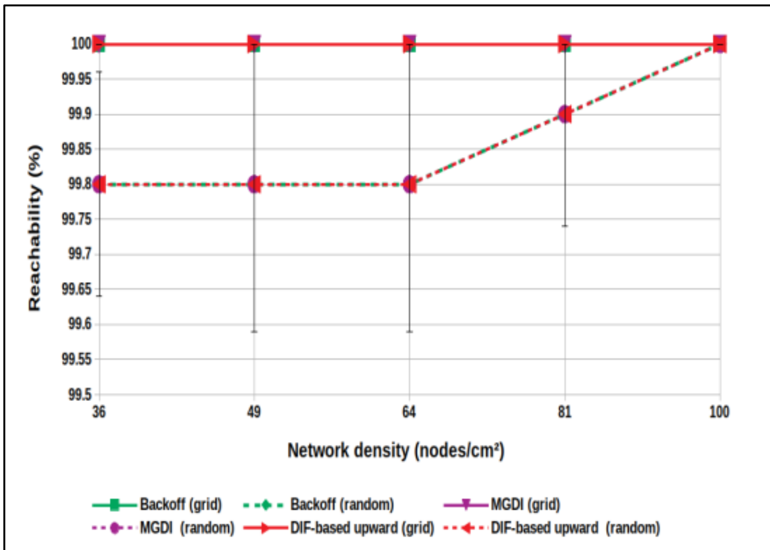


Fig. 6.124 : ARE of the compared schemes, versus the nanonetwork density.

Fig. 6.105: AE2ED of the compared schemes, versus the nanonetwork density.



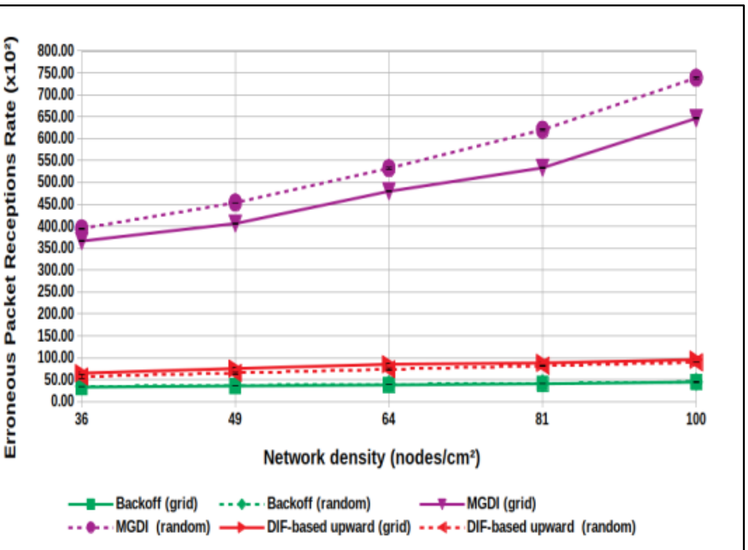


Fig. 6.86: Reachability of the compared schemes, versus the nanonetwork density.

Fig. 6.13 : EPRR of the compared schemes, versus the nanonetwork density.

In contrast, with CORONA scheme, the increase of nanonetwork density leads to the increase of forwarders, due to the increase of the number of nodes located between the communicating node-pairs. Fig. 16 shows that the residual energy in the whole nanonetwork is negatively affected by the increase of the network density, which generates significant sources of energy wastage, such as erroneous packet reception, redundant packet reception and overhearing. Thanks to the adopting counter-based mechanism and the selective selection of forwarders, the proposed scheme reduces the wastage of energy and maintains the highest residual energy. Fig. 17 shows that when the nanonetwork density increases the average end-to-end delay decreases. This makes sense because the increase of nanonetwork density reduces the hop-count distance between communicating nodes, limiting the length of paths traversed by each packet from the source node to the destination node. Despite, the shortest path could be among the alternative paths offered by CORONA, DEROUS shows less communication latency, because the length of its packet header is lower than the packet header of CORONA and the proposed scheme. On the other hand, due to the trade-off between energy consumption and delay, the proposed scheme offers a slightly longer delay.

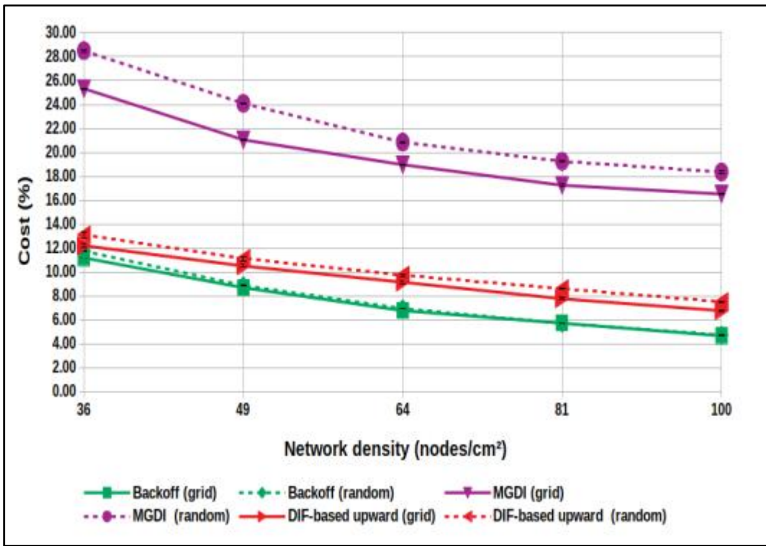


Fig. 6.14: Ratio of forwarders included for each scheme, versus the nanonetwork density.

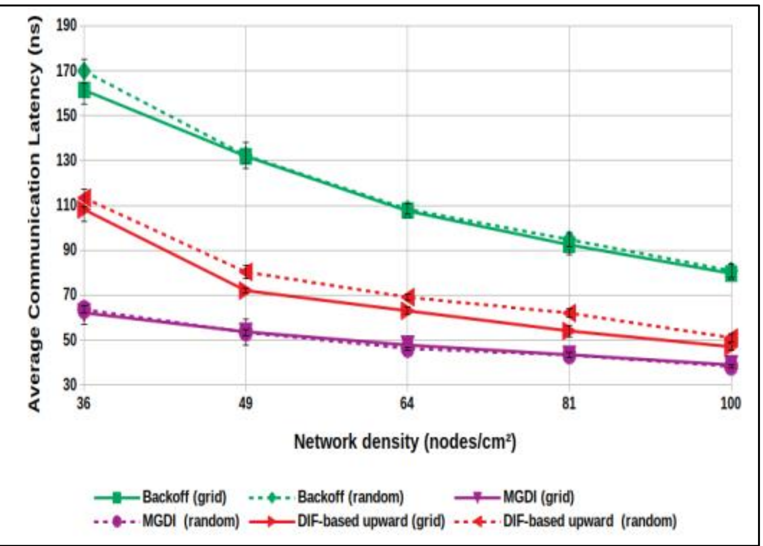


Fig. 6.19: Communication latency of the compared schemes, versus the nanonetwork density.

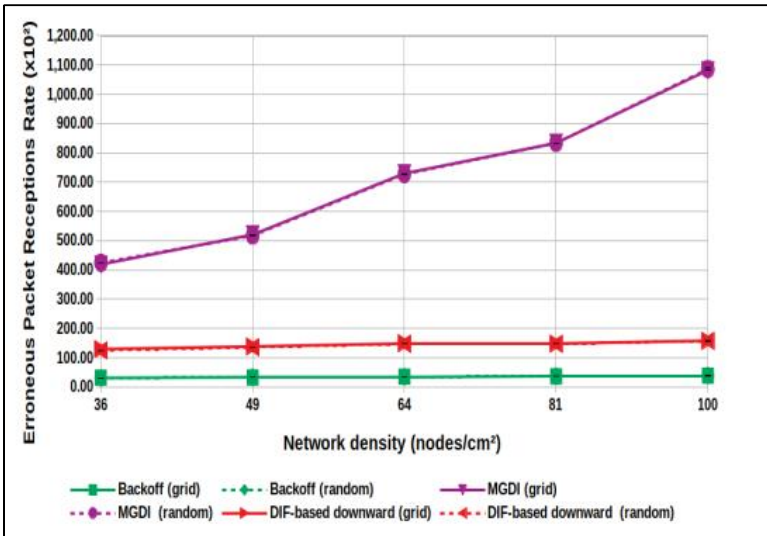


Fig. 6.160: EPRR of the compared schemes, versus the nanonetwork density.

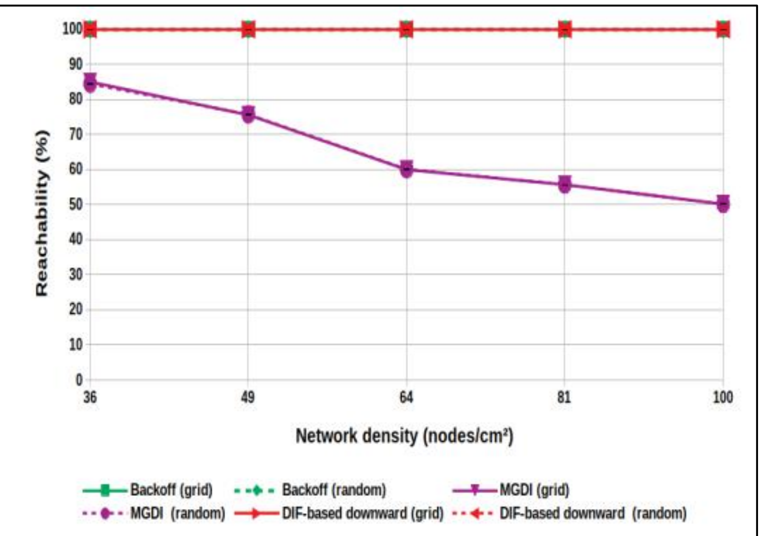


Fig. 6.215: Reachability of the compared schemes, versus the nanonetwork density.

6.3.4.3. Upward Scenario: varying nanonetwork density

In Fig. 6.16, it can be seen that the compared schemes show the same behavior. Regardless to the nanonetwork density, in grid layout, all generated packets reach the external entity. While, in random layout, the increase of density enables to improve the performance of the compared schemes up to 100%. Due to the appearance of new alternative paths resulting from the increase of density. However, as shown in Fig. 6.17, the increase of nanonetwork density is offset by a significant increase in the erroneous packet receptions rate, especially in MGDI. This is expected because, on one hand, MGDI includes a high number of nanodevices in the forwarding process, which the probability of being in the same area rising with the increase of density, leading to a high collision rate and fast nanodevice queue overflow. On the other hand, the proposed scheme and backoff flooding scheme treat efficiently with this drawback commonly found in flood-based schemes, by reducing the number of forwarding process and applying a safe random timeout before forwarding incoming packets. Simultaneously, as could be observed in Fig. 20, the increase of erroneous packet receptions rate decrease the rate of nodes participating in the forwarding process. In terms of communication latency, as shown in Fig. 21, the increase of nanonetworks density leads to the decrease of this metric, due to the diminution of the hop-count distance between communicating nodes. MGDI offers the less communication latency, thanks to its ray-like classification of forwarders, thus, packets travel in straight paths. However, over the increase of density, its communication latency reduces at a slight rate compared to the proposed scheme, due to the high rate of erroneous packet reception, affecting the straight paths. While, backoff flooding scheme shows the worst performance, due to the required waiting timeout before forwarding incoming packets.

6.3.4.4. Downward Scenario: varying nanonetwork density

Fig. 22 presents that MGDI suffers highly from erroneous packet receptions. Moreover, in downward communication, MGDI is subject to more erroneous packet receptions than in upward communication (see Fig. 19). MGDI routes the incoming packets from the external entity to reach all nanodevices in the network through ray-like paths towards the center. Accordingly, in each forwarding process, since it approaching the center, the forwarders become more near, leading to generate more collisions and nanodevice queue overflow, which prevent the incoming packets to reach to all nodes, as presented in Fig. 23. While the proposed scheme and backoff flooding scheme maintain a high reachability over the increasing of density, where all nodes receive the incoming packets. Thanks to the low number of forwarding process, as presented in Fig. 24, as well as the applied random timeout, reducing erroneous packet receptions rate. In Fig. 25, it can be observed that the backoff flooding scheme has the larger communication latency, due to its waiting timeout posed before forwarding any incoming packets, where this scheme reduces the number of forwarding process at the cost of communication latency. In contrast, the proposed scheme benefits from its routing mechanism by encouraging the classified forwarders with high residual energy to forward directly the incoming packet, while, applying an adjusted waiting time on the rest of forwarders before trying to participate in the forwarding process.

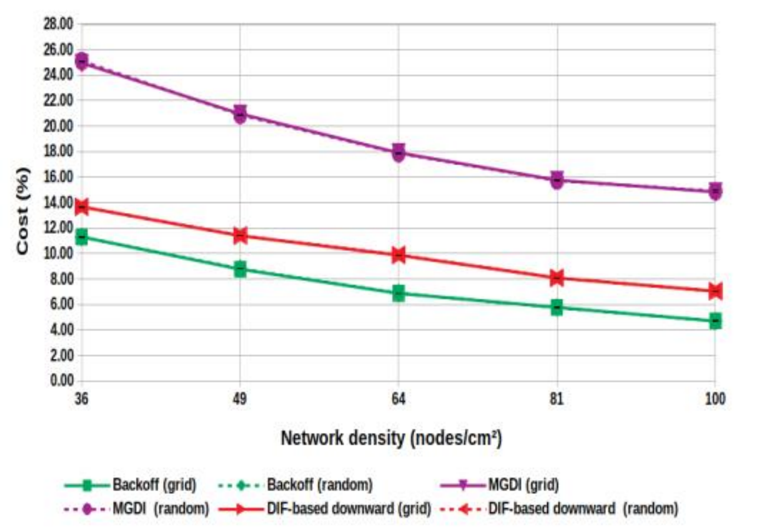


Fig. 6.182: Ratio of forwarders included for each scheme, versus the nanonetwork density.

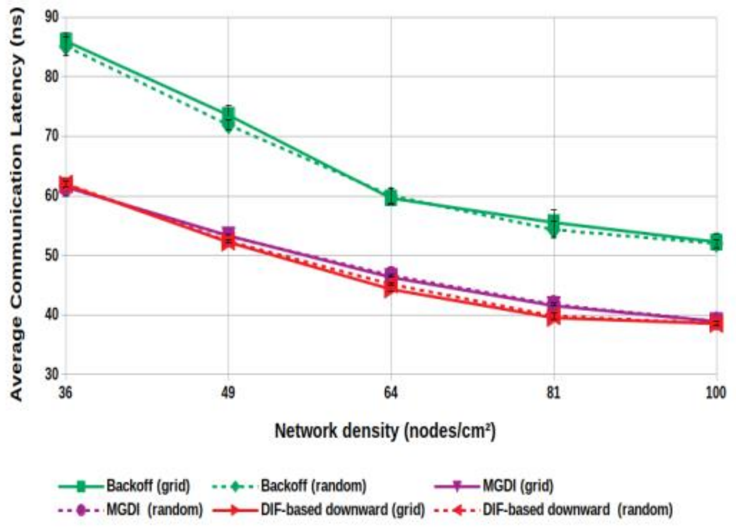


Fig. 6.18: Communication latency of the compared schemes, versus the nanonetwork density.

6.4 Conclusion

In this chapter, we introduced P2PAFS (Peer-to-Peer Addressing and Flooding System), a comprehensive framework designed to support three distinct communication modes — peer-to-peer, upward, and downward communication — in dense, homogeneous 2D nanonetworks. Unlike conventional routing schemes that primarily focus on data aggregation or assume sparse network deployments, P2PAFS adopts a unified communication framework tailored for emerging application domains such as Software-Defined Metamaterials (SDMs), Quantum Computing, and Wireless Networks In-Package. These domains demand robust and flexible communication strategies to facilitate localized data exchange, data dissemination to external controllers, and the reception of control directives. The proposed framework leverages a self-assigning geo-address system that enables each nanonode to autonomously determine its address based on its spatial coordinates without relying on complex routing tables or centralized control. This decentralized approach not only minimizes control overhead but also enhances network scalability in dense deployments. Additionally, P2PAFS employs a dynamic infrastructure (DIF) mechanism that allows nanonodes to selectively participate in forwarding operations, thereby optimizing energy consumption and extending network lifetime.

The simulation results demonstrate that P2PAFS effectively balances energy consumption, communication reliability, and delivery latency across all three communication modes. Specifically, the framework exhibits superior performance in terms of Packet Delivery Ratio (PDR), Average Residual Energy (ARE), and Average End-to-End Delay (AE2ED) when compared to conventional schemes such as CORONA and DEROUS. Moreover, the adoption of adjusted counter-based and probabilistic flooding techniques significantly mitigates the impact of the broadcast storm problem, reducing redundant transmissions while maintaining robust data delivery. For peer-to-peer communication, P2PAFS leverages selective flooding to minimize packet collisions and conserve energy, achieving higher PDR and lower latency even in dense network scenarios. In the upward communication mode, the DIF-based scheme ensures reliable data dissemination to external entities by employing controlled flooding mechanisms that prevent packet loss in high-density regions.

Similarly, the downward communication mode utilizes directed flooding to deliver control directives efficiently, ensuring that all nodes receive critical data with minimal delay.

Despite these gains, the analysis reveals that erroneous packet reception remains a key factor affecting overall performance, particularly in dense deployments where node density increases the likelihood of packet collisions. Therefore, future work will focus on further optimizing the forwarding decision-making process by incorporating cross-layer mechanisms that consider the physical and link layer characteristics. Additionally, the integration of handshake-based routing protocols could further mitigate the broadcast storm problem, reducing redundant transmissions while maintaining reliable data delivery across all communication modes.

Overall, the proposed P2PAFS framework represents a significant advancement in nanonetwork communication, effectively addressing the unique requirements of SDMs, quantum computing, and in-package wireless networks, where dense deployments demand robust, multi-modal communication frameworks that are both energy-efficient and scalable.

Chapter 7 QoS Analysis, Open Challenges and Future Directions

7.1 Introduction

The evaluation of Quality-of-Service (QoS) metrics in electromagnetic nano-networks serves as a crucial benchmark for assessing the performance and effectiveness of routing protocols. Unlike conventional wireless networks, electromagnetic nano-networks operate under severe constraints, including limited power capacity, restricted communication range, and dense node deployment. These inherent limitations significantly impact the ability to ensure reliable data transmission, minimize latency, and maintain energy efficiency — key QoS metrics that collectively determine the overall network performance**.** In the context of nano-networks, the significance of QoS evaluation is further amplified by the diverse application domains and operational scenarios, such as biomedical sensing, Software-Defined Metamaterials (SDMs), environmental monitoring, and quantum computing systems. Each of these domains imposes distinct communication requirements and performance expectations, necessitating the adoption of tailored routing strategies that can effectively balance QoS parameters under varying network conditions.

Four primary QoS metrics are pivotal in evaluating the performance of routing protocols in nano-networks. Reliability ensures data integrity across the network, particularly in applications where packet loss can result in critical information being lost or misinterpreted, such as biomedical and industrial monitoring. Latency focuses on minimizing the end-to-end delay in data transmission, which is crucial for real-time applications like flow-guided biomedical sensing and SDMs, where timely data delivery is paramount. Throughput quantifies the effective data rate across the network, especially in scenarios requiring continuous data streams, such as quantum computing systems and in-package wireless networks. Energy Efficiency is a fundamental concern in nano-networks, where nodes typically operate on limited power reserves, necessitating routing strategies that optimize energy consumption while ensuring sustained network operations.

In addition to these core metrics, nano-networks often require the consideration of supplementary QoS parameters. Thermal Regulation is essential in biomedical applications to prevent thermal buildup caused by THz transmissions, which can lead to tissue damage. Scalability assesses the protocol's ability to adapt to varying node densities, especially in ultra-dense deployments with thousands of nodes. Mobility Support addresses the challenge of maintaining reliable communication in dynamic networks where nodes may move within fluidic environments, such as blood vessels in biomedical systems. Congestion Control mitigates packet collisions and manages buffer occupancy, particularly in dense networks where simultaneous transmissions can lead to network congestion and data loss.

Previously, **Chapter 3** systematically classified contemporary routing protocols based on communication paradigms providing a structured perspective on how existing protocols align with specific communication modes. Building upon that foundation, the present chapter further aligns these protocols with the aforementioned QoS metrics to address the following research questions:

- **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?***".**

The chapter begins with **Section 7.2**, which examines the performance of data-centric communication protocols, focusing on how data aggregation, event-driven reporting, and centralized control influence reliability, latency, throughput, and energy efficiency in nano-networks. Subsequently, **Section 7.3** shifts the focus to peer-to-peer communication protocols, analyzing the trade-offs between energy conservation, latency reduction, and data delivery reliability in multi-hop routing scenarios. In **Section 7.4**, data dissemination protocols are evaluated, emphasizing the effectiveness of controlled flooding, adaptive retransmission, and probabilistic forwarding mechanisms in optimizing QoS metrics under ultra-dense deployment conditions. Following the QoS analysis, **Section 7.5** explores the emerging challenges that impede the development of efficient routing schemes capable of maintaining QoS in nano-networks. This section identifies critical challenges such as mobility support, scalability, thermal regulation, and congestion control, analyzing their implications for protocol design and data delivery reliability. Building on these identified challenges, **Section 7.6** outlines potential future directions, presenting cross-layer optimization strategies and highlighting the potential of AI/ML-driven adaptive frameworks to enhance routing performance in heterogeneous nano-network environments. Finally, **Section 7.7** synthesizes the findings, integrating insights from both the QoS analysis and the identified challenges, and delineates research gaps and design opportunities for next-generation QoS-aware routing protocols in electromagnetic nano-networks.

7.2 Data-Centric Communication Protocols: QoS Analysis

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 7.1, 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 7.1: QoS Analyse: Data-Centric Communication Protocols

Protocol	Reliability (PDR)	Latency	Throughput	Energy Efficiency	Additional QoS Metrics	Computational Complexity
E3A	Reasoning and Learning phases adapt routing paths to minimize packet loss.	Learning phase may introduce delays in dynamic conditions.	Energy-aware routing minimizes packet loss, enhancing data flow.	Adaptive routing minimizes energy use by prioritizing high-energy nodes as forwarders.	Thermal regulation through node exclusion and adaptive routing.	Moderate – requires CRNs to execute reasoning and learning processes.
4-DMDP	Dynamic routing adjusts paths based on flow dynamics, enhancing packet delivery.	Two-hop strategy reduces end-to-end delay.	Optimizes data flow by adapting to flow dynamics.	Flow-aware routing reduces unnecessary retransmissions, conserving node energy.	Mobility support through flow-guided routing and two-hop strategy.	High – centralized MDP calculations and state tracking increase complexity.
MILP	Optimizes paths to minimize packet loss using a centralized controller.	Centralized optimization may introduce computational delay.	Centralized control ensures optimal bandwidth allocation.	Centralized optimization reduces node-level processing, saving energy.	Scalability via centralized optimization and bandwidth allocation.	High – solving MILP is computationally intensive and scales poorly.
QL-MEC	Q-learning adjusts paths based on real-time network state to enhance PDR.	Q-learning training phase may increase latency.	Adaptive routing maximizes data flow through optimal paths.	Q-learning adjusts paths based on residual energy, preventing early depletion.	Buffer management through Q-learning and path adaptation.	High – Q-learning training is resource-intensive at the controller level.
TA-IBN	Threshold-based exclusion of overheated nodes maintains reliable data delivery.	Exclusion of overheated nodes may delay transmission.	Thermal regulation reduces packet loss, maintaining data flow.	Thermal regulation prevents overheating but may increase local energy use.	Thermal regulation by excluding overheated nodes.	Low – simple threshold checks and forwarding exclusion.
SA	Simulated Annealing selects optimal paths to prevent packet loss.	Simulated Annealing increases computation time for optimal paths.	Energy-aware routing reduces redundant data transmissions.	Simulated Annealing balances energy use by selecting optimal paths.	Data freshness by prioritizing high-priority nodes.	Moderate – SA involves probabilistic search but is locally executed.
TAEE	Temporal data correlation filters redundant transmissions, improving PDR.	Data correlation may delay data reporting in high-traffic scenarios.	Data filtering reduces unnecessary transmissions, increasing throughput.	Data filtering reduces redundant transmissions, conserving node energy.	Data freshness through temporal correlation and data suppression.	Low – data correlation logic is lightweight and node-local.
MRLSP	Kalman filter predicts link quality for reliable multi-hop routing.	Predictive routing reduces retransmissions, minimizing latency.	Predictive routing minimizes packet loss, maintaining data flow.	Predictive routing mitigates retransmissions, reducing energy drain.	Link stability prediction through Kalman filter.	High – Kalman filtering and fuzzy inference are resource-demanding.
EEPSN-Greedy	Cluster-based forwarding reduces packet loss through energy-aware node selection.	Single-hop communication within clusters minimizes delay.	Cluster-based forwarding reduces redundant transmissions, optimizing throughput.	Cluster-based forwarding conserves energy by reducing active transmitters.	Data freshness and congestion control via cluster-based forwarding.	Low – simple greedy selection and single-hop forwarding.
FGOR	Flow-guided routing prioritizes nodes moving toward the gateway, reducing packet loss.	Mobility gradient model reduces retransmissions, lowering delay.	Prioritized routing of critical data maintains steady data flow.	Mobility-based forwarding prioritizes nodes with sufficient energy for reliable delivery.	Mobility support using mobility gradient model and prioritized forwarding.	Moderate – mobility-aware relay selection and gradient tracking.
LCFSM	FSM-based control ensures reliable command dissemination by minimizing control packet loss.	Centralized control introduces minimal delay but requires periodic FSM updates.	Deterministic state transitions minimize unnecessary transmissions, optimizing throughput.	Low-complexity FSM structure reduces node-level processing and conserves energy.	Scalability through FSM state control and minimal node processing.	Low – FSM execution with pre-defined transitions is very lightweight.
ABC-OA	Swarm intelligence selects optimal forwarders	Data smoothing may delay transmission, but	Energy-aware node selection reduces redundant	Swarm intelligence balances data relevance and	Data freshness through opportunistic data	Moderate – combines data smoothing and

	based on residual energy, reducing packet loss.	opportunistic forwarding reduces overall latency.	transmissions, optimizing data flow.	residual energy, preventing premature depletion.	transmission and query response.	multi-criteria forwarder selection using ABC algorithm.

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 acceptable 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 7.1**, which provides a structured comparison of each protocol's impact on reliability, latency, throughput, and energy efficiency.

7.3 Peer-to-Peer Communication Protocols: QoS Analysis

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 7.2**, 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.

Table 7.2: QoS Analyse: 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.
ERT	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.

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 **Table 7.2**, outlining the trade-offs between reliability, latency, throughput, and energy efficiency in each protocol.

7.4 Data-Dissemination Communication Protocols: QoS Analysis

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 7.3**, which highlights the impact of each protocol on reliability, latency, throughput, and energy efficiency.

Table 7.3: QoS Analysis: Data-Dissemination Communication Protocols

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.

7.5 Challenges in QoS-Aware Routing for Nano-Networks

7.5.1 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?

Future Direction: Developing hybrid communication frameworks that dynamically adjust routing strategies based on residual energy levels and network conditions. The integration of opportunistic forwarding with lightweight learning algorithms can further extend network lifetime while sustaining QoS performance.

7.5.2 Scalability in Ultra-Dense Networks

As nano-networks are envisioned to support thousands of nodes in biomedical or environmental monitoring applications, mThis 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.anaging 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?

Future Direction: Implementing adaptive clustering mechanisms that dynamically adjust forwarding regions based on node density and traffic load. Additionally, integrating congestion-aware protocols that prioritize critical data packets during high-traffic periods can enhance scalability and network stability.

7.5.3 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?

Future Direction: Leveraging predictive models that incorporate flow dynamics and node mobility patterns to refine path selection. Machine learning models can further enhance adaptability by analyzing historical mobility data and adjusting routing paths to maintain QoS metrics like latency and packet delivery ratio (PDR).

7.5.4 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?

Future Direction: Developing lightweight routing algorithms that utilize heuristic optimization or compressed data structures to minimize computational overhead. Cross-layer optimization techniques that reduce redundant processing and integrate routing decisions with MAC and physical layers can further mitigate processing delays.

7.5.5 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?

Future Direction: Implementing thermal-aware routing mechanisms that dynamically adjust transmission power and packet size based on local temperature data. Additionally, integrating real-time temperature feedback can enable nodes to avoid overheated areas and optimize transmission paths accordingly.

7.5.6 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?

Future Direction: Developing multi-channel communication frameworks that dynamically allocate sub-bands based on real-time interference monitoring. Incorporating spectrum sensing techniques can further optimize channel utilization and mitigate packet collisions.

7.5.7 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?

Future Direction: Implementing lightweight encryption schemes that integrate probabilistic authentication mechanisms within routing decisions. Cross-layer security frameworks can further enhance data integrity by embedding verification checks at multiple protocol layers.

7.6 Emerging Research Directions In The Context Of Routing

The comprehensive analysis of routing protocols for electromagnetic nano-networks presented in this SLR reveals several critical research gaps that, if addressed, can significantly advance the state-of-the-art in QoS-aware routing. In this section, we delve into the emerging research directions, discussing them in the context of the surveyed protocols and their limitations while aligning with the broader literature.

7.6.1 Cross-Layer Optimization in Nano-Networks

Current protocols predominantly focus on the network layer, optimizing routing paths based on criteria such as residual energy, link quality, and hop count. Protocols such as EEPSN-Greedy**,** EECORONA, and MILP prioritize energy efficiency through network-centric mechanisms. However, they neglect cross-layer dependencies, particularly with the MAC and physical layers, which are crucial in electromagnetic nano-networks operating in the THz band.

Research Gap and Rationale:

- The absence of integrated cross-layer optimization frameworks results in suboptimal routing decisions, as routing paths are selected without considering channel access, signal modulation, or temperature control at the physical layer.
- The unique characteristics of the THz band, such as molecular absorption and high path loss, necessitate adaptive routing strategies that can dynamically adjust transmission power and packet size based on channel conditions.

Future Direction:

- Developing cross-layer frameworks that jointly optimize routing paths, transmission power, and MAC scheduling to balance energy consumption, throughput, and latency.
- Integration of thermal management protocols (e.g., TA-IBN and SA) with energy-aware routing schemes to simultaneously address overheating and energy depletion in biomedical nano-networks.
- Implementing predictive models that utilize channel state information (CSI) to select optimal sub-bands, thereby mitigating interference and optimizing data delivery.

Existing Literature Insight:

- Prior studies (e.g., Alshorbaji et al., 2024) introduced MILP to optimize routing and sub-band allocation. However, the centralized nature and computational complexity limit its scalability, highlighting the need for more decentralized, cross-layer approaches.

7.6.2 Machine Learning-Driven Adaptive Routing

Machine learning (ML) techniques have gained prominence in conventional wireless networks to optimize routing under dynamic network conditions. However, their integration in nano-networks remains underexplored, primarily due to computational and energy constraints. The use of ML in protocols such as QL-MEC and MDR-RL illustrates the potential of reinforcement learning (RL) in enhancing routing decisions based on historical data and evolving network conditions.

Research Gap and Rationale:

- Current RL-based schemes like QL-MEC and MDR-RL require centralized training and periodic updates, imposing significant communication overhead.
- While these protocols optimize path selection based on node energy levels and link quality, they do not consider mobility patterns, thermal regulation, or multi-objective optimization (e.g., energy vs. PDR vs. latency).

Future Direction:

- Development of lightweight ML algorithms (e.g., federated learning or edge RL) that distribute training across nodes, reducing communication overhead and enhancing scalability.
- Implementing transfer learning techniques that allow nodes to learn from prior routing experiences, enabling quicker adaptation to dynamic network conditions.
- Integrating predictive ML models that utilize flow dynamics (e.g., 4-DMDP and FGOR) to optimize path selection in mobile, flow-guided nano-networks.

Existing Literature Insight:

- While FGOR and 4-DMDP consider flow-guided routing, the integration of predictive ML models could enhance path selection by accounting for mobility trends, blood flow velocity, and node density fluctuations.

7.6.3 Hybrid Communication Frameworks

The communication paradigms identified in this SLR (Data-Centric, Peer-to-Peer, Data Dissemination) are treated independently in existing protocols. However, integrating these paradigms into a unified framework can significantly improve network performance by enabling adaptive communication modes.

Research Gap and Rationale:

- Current protocols, such as LCFSM**,** PBPD, and RFS, are designed for specific communication modes, limiting their applicability in heterogeneous network environments where nodes may need to switch between data-centric, peer-to-peer, and dissemination modes.

- Existing hybrid schemes, such as ABC-OA, are limited to single-hop opportunistic communication, lacking mechanisms for dynamic adaptation based on network density or node energy levels.

Future Direction:

- Designing hybrid frameworks that dynamically adjust communication modes based on network conditions (e.g., density, energy distribution, data criticality).
- Integrating context-aware mechanisms that enable nodes to autonomously switch between data-centric, peer-to-peer, and dissemination modes, optimizing QoS metrics such as latency and packet delivery ratio (PDR).
- Implementing opportunistic multi-hop routing schemes that combine relay selection in data-centric communication with peer-to-peer coordination for congestion management.

Existing Literature Insight:

- ABC-OA leverages swarm intelligence for data smoothing and query-based communication but remains confined to single-hop communication. Expanding this framework to multi-hop scenarios using adaptive relay selection could further enhance QoS in dynamic environments.

7.6.4 Multi-Objective Optimization (MOO) in QoS-Aware Routing

Most existing protocols focus on a single QoS metric, typically energy efficiency or PDR. However, achieving optimal network performance requires balancing multiple, often conflicting objectives, such as energy consumption, latency, and throughput.

Research Gap and Rationale:

- Protocols like MILP and QL-MEC consider multi-objective optimization in a centralized framework, which is computationally intensive and unsuitable for large-scale networks.
- The lack of decentralized MOO frameworks hinders scalability, as resource-constrained nodes struggle to handle multiple objective functions simultaneously.

Future Direction:

- Developing decentralized MOO frameworks that leverage distributed computing and heuristic optimization (e.g., genetic algorithms or ant colony optimization).
- Implementing fuzzy logic-based MOO schemes (e.g., as in MRLSP) that dynamically adjust routing paths based on evolving network states (e.g., node energy, link stability, thermal conditions).
- Applying Pareto-based optimization to balance multiple QoS metrics without overwhelming node resources.

Existing Literature Insight:

- MRLSP employs fuzzy logic for link state prediction but focuses solely on reliability and energy consumption. Expanding this framework to include latency and throughput as additional objectives could provide a more comprehensive QoS model.

7.6.5 Interference and Channel Utilization in THz Band

The THz band is characterized by high molecular absorption and path loss, making interference management a critical concern in nano-networks. Protocols like MILP and ERT address interference through sub-band allocation and timing-based forwarding; however, they are limited to static or semi-static network conditions.

Research Gap and Rationale:

- The lack of dynamic interference management frameworks prevents effective channel utilization in dense, mobile networks where interference patterns fluctuate rapidly.
- Existing protocols do not consider inter-channel coordination, leading to overlapping transmissions and increased packet collisions.

Future Direction:

- Developing multi-channel communication frameworks that dynamically allocate sub-bands based on real-time interference monitoring.
- Implementing spectrum sensing and cognitive radio techniques to optimize channel selection and mitigate inter-channel interference.
- Integrating flow-aware interference management (e.g., FGOR) to dynamically adjust transmission power based on node mobility and flow direction.

Existing Literature Insight:

- ERT employs timing-based forwarding to mitigate interference but is limited to static nodes. Incorporating mobility and flow dynamics can further optimize interference management in biomedical nano-networks.

7.6.6 Secure and Reliable Data Transmission

Security remains a relatively unexplored area in nano-network routing, despite its importance in biomedical applications. Existing protocols focus primarily on PDR and energy efficiency, neglecting data integrity and authentication.

Research Gap and Rationale:

- Protocols like ERA-SDN and SR-ANS implement probabilistic retransmissions to ensure data delivery but do not include mechanisms for data integrity verification or security against malicious nodes.

Future Direction:

- Incorporating lightweight encryption and authentication mechanisms within routing decisions to safeguard data without imposing excessive overhead.
- Implementing secure routing frameworks that detect and isolate malicious nodes, ensuring data integrity in peer-to-peer and data dissemination communications.

- Integrating cross-layer security protocols that leverage signal characteristics (e.g., timing, frequency) for authentication.

Existing Literature Insight:

- While ERA-SDN improves PDR in asynchronous networks, incorporating security checks during retransmission can further enhance reliability and data integrity.

7.7 Synthesis

The comprehensive analysis of routing protocols across the three communication paradigms provides valuable insights into how current schemes address key Quality-of-Service (QoS) metrics in electromagnetic nano-networks. The evaluation underscores the importance of energy efficiency, reliability, latency, and throughput as fundamental performance indicators in nano-network environments characterized by resource constraints and dense node deployments. A prominent trend observed across the analyzed protocols is the emphasis on energy efficiency as a primary design objective. Given the inherent power limitations of nanoscale devices, routing schemes are increasingly adopting energy-aware forwarding mechanisms, integrating probabilistic, counter-based, and adaptive retransmission strategies to mitigate redundant transmissions and minimize energy consumption. For instance, protocols that implement selective forwarding based on residual energy levels not only conserve node energy but also extend network lifetime, a critical consideration in high-density deployments where rapid energy depletion can lead to network partitioning.

Despite these advances, the analysis reveals that energy efficiency often comes at the expense of latency and throughput, particularly in data-centric communication protocols where data aggregation and centralized processing introduce significant transmission delays. This trade-off is particularly pronounced in protocols that rely on event-driven communication or centralized querying, where data packets are held until specific sensing events occur or command directives are received. Consequently, while these protocols effectively reduce redundant transmissions and optimize energy usage, they also risk increasing end-to-end delay, thereby compromising latency-sensitive applications such as biomedical sensing and SDMs. In contrast, peer-to-peer communication protocols demonstrate significant improvements in latency reduction and data delivery reliability by enabling direct node-to-node interactions without relying on centralized entities. However, the analysis reveals that the scalability of peer-to-peer schemes remains a critical challenge, particularly in ultra-dense networks where simultaneous peer-to-peer transmissions can escalate congestion and packet collisions, leading to degraded network throughput. This limitation is particularly evident in protocols that implement probabilistic or counter-based flooding mechanisms, where the trade-off between energy conservation and reliable data delivery becomes more pronounced as node density increases. Data dissemination communication protocols, on the other hand, exhibit considerable potential **in** optimizing network-wide data propagation through controlled flooding and structured broadcasting techniques. Protocols that implement dynamic infrastructure (DIF) mechanisms and adaptive retransmission strategies effectively regulate the number of forwarding nodes, thereby reducing congestion and mitigating the broadcast storm problem. However, the synthesis reveals that data dissemination schemes must also consider thermal regulation and congestion control, particularly in high-density biomedical networks where excessive retransmissions can induce thermal buildup and exacerbate packet collisions. Additionally, the analysis highlights emerging design patterns that reflect ongoing efforts to address cross-layer optimization and adaptive routing in dynamic network conditions. Protocols that integrate machine learning-based predictive mechanisms and reinforcement learning strategies demonstrate promising results in predicting optimal forwarding paths, adjusting retransmission probabilities, and balancing energy consumption across nodes. These adaptive schemes are particularly relevant in dynamic environments such as flow-guided biomedical networks and quantum computing systems, where network topology, node mobility, and data traffic may fluctuate rapidly.

In light of these advancements, several key challenges remain unaddressed. Mobility support remains a significant gap, as most protocols are designed for static networks, neglecting the impact of node mobility on communication reliability. Implementing mobility-aware routing mechanisms that can dynamically adjust forwarding paths based on node movement patterns and link quality is essential to maintain data integrity in dynamic network settings. Scalability also emerges as a major concern in ultra-dense networks, where excessive retransmissions can accelerate energy depletion and network congestion.

Addressing this challenge requires scalability-centric strategies, such as adaptive flooding control, probabilistic forwarding, and DIF mechanisms, to manage data dissemination effectively and prevent broadcast storms. Thermal regulation is another underexplored aspect, particularly in biomedical applications, where prolonged THz transmissions can lead to thermal buildup, increasing the risk of tissue damage. Incorporating thermal-aware communication strategies that adjust transmission power, packet scheduling, and data dissemination intensity is vital for preventing overheating while maintaining data delivery reliability. Moreover, the integration of cross-layer optimization frameworks remains limited. Current protocols often function independently across the physical, MAC, and network layers, resulting in suboptimal routing decisions and increased latency. Implementing cross-layer frameworks that coordinate link selection, retransmission control, and power allocation can significantly enhance communication reliability and energy efficiency, particularly in multi-hop scenarios. Lastly, the potential of AI/ML-driven adaptive routing offers a promising pathway to address the dynamic and unpredictable nature of nano-networks. Predictive models and reinforcement learning can anticipate network dynamics, link stability, and traffic congestion, enabling real-time adjustment of forwarding paths. However, the computational overhead and data requirements of AI-based models pose significant challenges, necessitating the development of lightweight learning algorithms tailored for resource-constrained nanonodes.

Overall, the synthesis emphasizes the need for multi-objective routing protocols that balance QoS metrics while addressing the unique operational challenges of dense electromagnetic nano-networks. The findings from this chapter provide a strategic foundation for advancing next-generation QoS-aware routing protocols, integrating mobility support, scalability mechanisms, thermal regulation, cross-layer optimization, and AI/ML-driven adaptive frameworks. When effectively combined, these components can significantly enhance the resilience, adaptability, and scalability of nano-network routing protocols, paving the way for future research in complex, heterogeneous deployment scenarios.

III

GENERAL

CONCLUSION

Chapter 8
Conclusion and Synthesis

8.1 Summary of Contributions

This thesis addresses the critical challenges associated with Quality of Service (QoS) in electromagnetic nano-networks, characterized by severe power limitations, ultra-dense node deployments, and limited communication ranges. Through a systematic literature review (SLR)**,** existing routing protocols were classified based on data-centric, peer-to-peer, and data dissemination paradigms, revealing key gaps in scalability, multi-mode communication support, and thermal regulation. To bridge these gaps, three novel routing protocols were developed and extensively evaluated to enhance data delivery reliability, energy efficiency, and communication flexibility in dense nano-networks:

1. **EECORONA:**

   This work introduces a set of energy-efficient flood-based protocols designed to reduce redundant transmissions and extend network lifetime **through** selective forwarding and probabilistic retransmission control. It is the first protocol in nano-networking to specifically address the severe power limitations of nanonodes in dense 2D deployments. EECORONA not only minimizes energy consumption but **also** maintains high packet delivery reliability, establishing itself as a benchmark for energy-aware routing in resource-constrained nano-networks.

2. **DCCORONA:**

   Addressing the scalability and congestion issues in ultra-dense networks, DCCORONA employs a cluster-based multi-hop routing framework that leverages adaptive clustering and energy-aware cluster head selection. Nodes self-organize based on geographic coordinates, and cluster heads are selected dynamically based on residual energy and node centrality. DCCORONA is the first distributed, cluster-based multi-hop routing scheme for homogeneous 2D nano-networks, effectively balancing communication loads and enhancing data delivery reliability while mitigating congestion.

3. **P2PAFS:**

   P2PAFS is the first framework to simultaneously support peer-to-peer, upward, and downward communication modes within a single protocol architecture. Integrating dynamic infrastructure (DIF) mechanisms and adaptive flooding control, P2PAFS enables flexible routing across heterogeneous network topologies, making it particularly applicable to scenarios such as Software-Defined Metamaterials (SDMs), in-package wireless systems, and biomedical monitoring. The framework's multi-mode communication capability provides a robust, adaptive routing solution for dynamic nano-networks.

Each proposed protocol was evaluated through comprehensive simulations using nano-sim tool on NS-3, measuring Packet Delivery Ratio (PDR), latency, throughput, and energy efficiency. Results demonstrate that the proposed schemes achieve significant improvements in data delivery reliability and energy conservation, positioning them as effective solutions for next-generation QoS-aware nano-networks**.**

8.2 Research Outlook and Recommendations

While the proposed protocols successfully address key QoS challenges in dense electromagnetic nano-networks, several open research questions and unresolved challenges warrant further investigation:

1. **Mobility Support in Biomedical Networks:**
   - The proposed schemes are primarily designed **for** static or semi-static networks. However, in applications such as biomedical sensing and in-body nano-networks, nodes may traverse fluidic or vascular environments, introducing unpredictable link dynamics and frequent topology changes. Future work should explore mobility-aware routing mechanisms that dynamically adjust forwarding paths based on node mobility patterns, link stability, and network density. Implementing predictive models to anticipate node movement and proactively adjust routing paths can enhance data delivery reliability in dynamic networks.

2. **Scalability in Ultra-Dense Deployments:**

   As nano-networks scale to include thousands or millions of nodes, the risk of network congestion and data redundancy intensifies. Future protocols should incorporate scalability-centric mechanisms, including adaptive clustering, probabilistic forwarding, and congestion control strategies, to regulate node participation and minimize redundant transmissions in high-density scenarios. Additionally, exploring hierarchical routing structures that combine localized clustering with global aggregation may provide an effective solution for managing data dissemination in large-scale networks.

3. **Thermal Regulation in THz Communication:**

   THz communication offers ultra-high data rates but also presents risks of thermal buildup due to molecular absorption and scattering, particularly in biomedical and in-package wireless networks. **Developing** thermal-aware routing protocols **that** adjust transmission power, control data dissemination intensity, and regulate node activity is crucial to prevent overheating and ensure safe data transmission in temperature-sensitive environments.

4. **Cross-Layer Optimization:**

   Current routing protocols operate independently across network layers, leading to suboptimal routing decisions and increased latency. Integrating cross-layer optimization frameworks can significantly enhance communication reliability and energy efficiency, particularly in multi-hop networks where link quality, energy levels, and data traffic patterns fluctuate dynamically. Cross-layer frameworks should coordinate link selection, retransmission control, and power allocation, particularly in dense networks with multi-hop communication paths**.**

5. **AI/ML-Driven Adaptive Routing:**

   The unpredictable nature of nano-networks presents an opportunity for the integration of AI/ML-driven adaptive routing mechanisms. Implementing predictive models and reinforcement learning frameworks can anticipate network dynamics, link stability, and traffic congestion, enabling real-time path adjustments and optimal forwarding decisions. However, given the limited computational resources of nanonodes, future studies should focus on lightweight ML models **that** balance learning accuracy and energy overhead.

6. **Security and Privacy Considerations:**

   With the expansion of nano-networks in biomedical and quantum computing systems, security and privacy risks become more pronounced. Future protocols should incorporate lightweight encryption, authentication, and anomaly detection mechanisms to safeguard data integrity and prevent node compromise without imposing excessive energy overhead.

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