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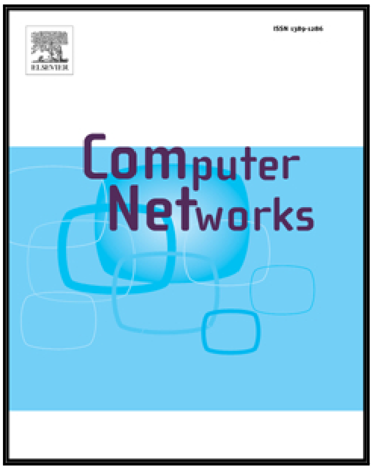

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Probability-based Path Discovery Protocol for Electromagnetic Nano-networks

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Abstract

One of the major challenges for nano-network is the forfeit of communication protocols to exploit the potential communication between nano-machines forming fully operational nano-network. Because nano-machines face some restrictions such as limited processing power and confined computing capabilities, up-to-date nano-machines cannot perceive partial or full routing tables, which are the main decision-makers for data routing in legacy communication networks. The reason is that creating and updating routing tables continuously require adequate processing power with sufficient memory and computing capabilities, which is not the case of nano-nodes. So, new innovative routing schemes have to be proposed for nano-networks to deal with such extremely low resources. This paper focuses on decoupling the routing intelligence from nano-network towards a computational architecture using Software Defined Networking (SDN) and Network Function Virtualization (NFV) technologies by externalizing routing decisions and complex computations from nano-nodes to be fully compiled externally. Moreover, the paper proposes a probability-based path discovery protocol denoted by (PBPD) for electromagnetic nano-nodes suitable for dynamic nano-network applications. The performance of the proposed protocol is evaluated and compared with other routing protocols discussed in the literature. The proposed scheme provides low energy consumption inside nano-nodes and low computational complexity thanks to SDN/NFV system.

Keywords: Nano-network, Packet routing, Internet of nano-things, Software defined networking, Network function virtualization, Virtual routing

Abbreviations

AODV	Ad hoc On-Demand Distance Vector
BAN	Body Area Network
BGP	Border Gateway Protocol
CORONA	Coordinate and Routing system for Nano-networks
CT	Computed Tomography
DEDeN	Density Estimator for Dense Networks
DEROUS	Deployable Routing System
DIF	Dynamic Infrastructure
DSR	Dynamic Source Routing
E3A	Enhanced Energy-Efficient Algorithm
ECR	Energy Conservation Routing
ESC	Elastic Services Controller
GPS	Global Positioning System
IoNT	Internet of Nano-Things
IoT	Internet of Things
IS-IS	Intermediate System to Intermediate System
KPI	Key Performance Indicator
MANET	Mobile Ad hoc Network
MHTD	Multi-Hop Transmission Decision
MPLS	Multi-protocol Label Switching
NetConf	Network Configuration
NFV	Network Function Virtualization
NFVI	Network Function Virtualization Infrastructure
NFVO	Network Function Virtualization Orchestrator
NM	Nano-machine
NoCs	Networks-on-Chips
NR	Nano-router
NSO	Network Services Orchestrator
OppNet	Opportunistic Network
OSM	Open Source MANO
OSPF	Open Shortest Path First
OVSDB	Open vSwitch Database
PBPD	Probability-Based Path Discovery
RaaS	Routing-as-a-Service
RFID	Radio Frequency Identification
RFV	Routing Function Virtualization
SDMs	Software Defined Materials
SDN	Software Defined Networking

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SFC	Service Function Chaining
SLR	Stateless Linear Routing
SNMP	Simple Network Management Protocol
TDD	Targeted Drug Delivery
VIM	Virtual Infrastructure Manager
VNF	Virtual Network Function
VNFFG	Virtual Network Function Forwarding Graph
VNFM	Virtual Network Function Manager
WBSNs	Wireless Body Sensor Networks
WNSNs	Wireless Nano-Sensors Networks
WSN	Wireless Sensor Network

1. Introduction

Routing in nano-network requires new strategies to deal with different challenges and limitations associated with the communication between nano-machines. Processing capabilities, energy consumption, lossy wireless channels and hardware manufacturing are among these challenges [1]. Nano-machines will communicate with each other to i) exchange and forward gathered information, ii) coordinate their joint actions and iii) interface with other biological and/or artificial systems. Hence, nano-machines shall be able to forward signals and/or packets [2].

Recently, nano-technology has been emerged to provide new opportunities for sensing and actuating using nano-machines [3]. Many efforts have been made in research to implement nano-scale machines, which are defined as mechanical or electromechanical devices, that can perform very simple tasks and useful functions using components in the nano-meter scale [4]. Nano-sensors/devices can sense, compute and communicate into networks or the Internet enabling advanced applications of nano-technology in the biomedical, environmental and industrial fields [5]. In the biomedical field, nano-nodes can be used in medical treatment applications of in-body networks, where Targeted Drug Delivery (TDD) is one of these major applications [6] [7]. Likewise, nano-nodes can be used in health tracking systems and human bond communication, which is a concept that can be practically useful in healthcare and safety applications enabling the idea of patient monitoring continuously and remotely [8]. By hooking up to wearable health trackers, medical persons can monitor real-time measurements of the human body like heartbeats rate, blood pressure, breath tests and get an early detection of sickness [7] [9]. In the environmental field, by releasing nano-nodes into the air, they can play an important role in monitoring the spread of viruses and diseases in public locations [9]. Besides, nano-technology has the potential to bring important changes in fertilizers and pesticide delivery in the agriculture industry [10]. In the industrial field, nano-technology can transform the food industry by bringing changes in the production, processing, packaging and consumption of food. Usage of nano-technology in these processes ensures the safety of food products, creates healthy food and enhances the nutritional quality, where smart food packaging systems can be developed to increases the shelf-life of food products by developing active anti-microbic surfaces. Several companies have started to develop smart packaging systems to prevent drying of food content and protect it from oxygen and moisture [10]. Furthermore, in the military field, nano-technology can be used in surveillance against chemical attacks at the nano-scale [11].

The collaboration among nano-machines to extend the performance of a single stand-alone nano-machine beyond executing very simple tasks has become a reality through nano-networks. This collaboration requires data transmission between nano-devices, which face some restrictions, because of constraints in processing, storage, energy and communication range capabilities, in addition to different sources of noise in specific applications such as signal molecular absorption inside the human body network [12]. All of these factors make the communication of nano-machines impracticable most of the time, whether between themselves or to the Internet. So, routing in nano-network using multi-hop communication becomes indispensable to keep proper and effective communication among nano-machines. Compared to legacy network, fixed-function hardware appliances, e.g., routers, switches, firewalls and load balancers have control plane, data plane and management plane, which represent the main factors to select the best routing decision and make data forwarding based on different embedded algorithms, while up-to-date nano-machines cannot deal with partial or full routing tables like traditional network machines. So, a simple routing technique with low processing capacity and low energy consumption will be more adequate to propose a routing protocol scheme in the nano-network's context.

In today's networking industry, continuous enhancement of network programmability and next-generation network technologies, e.g., SDN and NFV have emerged to increase the flexibility of network services deployment and integration within the operators' networks. This is achieved by implementing network functions through software, avoiding specific hardware devices. NFV applies to any network function to simplify the management of heterogeneous hardware platforms, while SDN technology separates the data forwarding plane and the corresponding control plane, which is implemented in a separate SDN controller. With SDN/NFV approach, the network will be dynamically programmable, and administrators will be able to build different solutions to manage and control infrastructure services remotely [13]. The major objectives of this paper are as follows:

- Virtualize and externalize the routing decisions from nano-nodes making the routing knowledge to be logically centralized externally over a powerful computational SDN/NFV system architecture, which had been proposed in our previous work [14]. This SDN/NFV system is responsible for calculating the best path to the destination nano-router, as this cannot be achieved internally on the nano-network because of their computing limitations.

- Propose a probability-based path discovery protocol in a random dynamic electromagnetic nano-network. This protocol will be compiled on the external SDN/NFV system, and it follows a hierarchical structure that leads to energy consumption reduction inside nano-nodes, besides providing low computational complexity and good scalability. The strategy of this protocol is based on the probability density of nano-routers to estimate their location based on some assumptions and hypotheses.

The rest of the paper is organized as follows. The literature review and related work are presented in Section 2. The proposed virtual routing function of nano-networks is presented in Section 3. The proposed path discovery protocol for electromagnetic nano-networks is presented in Section 4. The analytical model of the proposed scheme is presented in Section 5. Then, performance evaluation of the proposed scheme is illustrated in Section 6, followed by the conclusion and future work in Section 7.

2. LITERATURE REVIEW AND RELATED WORK

Different approaches in the literature focused on designing and developing routing protocols for electromagnetic nano-networks. In this section, we briefly discuss the recent relevant work in this approach with the main focus on simple flooding protocols, proximity routing protocols, routing protocols adapted from ad hoc networks and energy conservation routing protocols. Then, we will discuss the routing capability in the SDN/NFV system showing how SDN and NFV technologies interlock together to add a functional value for the nano-network and the overall computational architecture.

2.1. *Simple flooding protocols*

Simple flooding protocols are the initial proposed routing protocols for nano-network. They are motivated due to their simplicity, which adapts to the capabilities of nano-nodes. These protocols are flood-based, where each nano-node receives the packet and checks if the packet was previously received. If yes, the packet is ignored, otherwise the nano-node broadcasts the receiving packet to all its neighbors [3]. These flooding schemes are very costly in terms of wasted bandwidth and collisions due to excessive messages that cause broadcast storm problem, which makes excessive retransmission, thus increasing energy consumption. Hence, reducing redundant transmission is one of the primary issues need to be solved for these protocols [12].

2.2. *Proximity routing protocols*

Proximity routing protocols are proposed to improve the performance of simple flooding schemes by controlling the number of neighboring nodes participated in retransmissions by introducing an approach called Dynamic Infrastructure (DIF). The main idea of DIF is to mitigate broadcasting, where nano-nodes with a good reception quality can act as transmitters, while the remaining nano-nodes revert to receiving-only mode [15]. These routing protocols require addresses for nano-machines, besides their corresponding location. Each node shall be individually identified and distinguish its location relative to its neighboring nodes. Obviously, nano-networks cannot use traditional localization techniques, such as Global Positioning System (GPS) units, as they require some computational capacity, which leads to a dramatic degradation in energy consumption. So, new localization techniques for nano-machines are still open areas of research [16]. Some work in the literature had been proposed to estimate the number of neighboring nodes. Arrabal et al. [17] presented a distributed algorithm called Density Estimator for Dense Networks (DEDeN) in very dense electromagnetic wireless nano-networks. This algorithm allows a nano-node to estimate the number of its neighbors (neighborhood density). While in [18], Arrabal et al. proposed a broadcasting scheme for dense nano-networks by using the estimator of the number of neighbors, which was proposed in [17]. They showed on a random dense network how it reduces the number of packets exchanged compared to other proposed methods in the literature.

It is worth mentioning that proximity routing protocols have some limitations in the practical deployment of dynamic nano-network, because their algorithms assume fixed nano-network topology. On the other hand, these techniques require addresses for all nano-nodes, which adds additional challenges [16]. Examples of these protocols are Coordinate and Routing system for nano-networks (CORONA) and Stateless Linear Routing (SLR) [12]. Tsioliaridou et al. [15] presented CORONA as a geographic flooding protocol, where nano-network is assumed to consist of two types; anchor nodes and user nodes. Anchor nodes have higher communication and processing capabilities than user nodes. User nodes are required to localize their position relative to these anchor nodes. This scheme assumes square fixed network topology with four anchors are located at the vertices of the square corners, and it operates in two phases: setup phase and operation phase. The setup phase is designed to assist user nodes in measuring their related distances from the anchors. While in the operation phase, a source node selects the anchor nodes and incorporates this information in a packet header. A receiving node checks its location, the destination location and source location to decide on either forwarding or dropping the packet. In [19], Tsioliaridou et al. extended their work to be used on multi-hop, peer-to-peer 3-D rectangular network space called SLR, which is a coordinate-based routing protocol designed for 3-D nano-networks. The coordinate system of SLR is extended from CORONA and assigns 3-D coordinates to nano-nodes. The proposed addressing scheme requires minimal overhead, as it defines a geometric volume within the space, where each node obtains its position in the network. While in [1], Tsioliaridou et al. extended this work to be applied to different applications in material monitoring and programmatic property tuning.

2.3. *Routing protocols adapted from ad hoc networks*

An ad hoc network is a set of portable nodes that can establish a communication anytime and anywhere between themselves. Communication among nano-machines is developed in the direction of ad hoc networks, because of conceptual similarities between nano-networks and ad hoc networks-on-chips (NoCs) or macro-scale Wireless Sensor Networks (WSNs), which is a particular type of ad hoc networks [3]. Some of these similarities are the rapid topology changes, unreliable wireless channels, network congestion and the ability to be reconfigurable and self-organized. However, restrictions of nano-nodes in terms of computational power, memory and energy consumption along with the expected high number of nano-machines participated to form a nano-network give rise to different protocols and networking design issues, which require to maintain simplicity in designing and implementation [15].

A set of routing protocols is needed in ad hoc networks to classify the routes between nodes properly to deliver a message from the source to the destination in an efficient way under certain energy and complexity constraints. Usually, they aim to minimize energy consumption and maximize the lifetime of the network, however routing protocols with good performance have high computational complexity. In general, NoCs and WSNs are considered much more powerful nodes than nano-nodes, so routing protocols developed for them are not suitable to be applied directly for nano-network. Hence, these routing protocols were adapted and modified to be used into nano-networks to simplify the forwarding process and find the best path to the destination, accordingly improve the performance of nano-networks [20].

One of these adapted protocols is Ad hoc On-Demand Distance Vector (AODV). AODV follows a flooding technique for route discovery mechanism, when a certain node requires to send a packet to another node, it broadcasts route request message to all its neighbors. Then, the neighbor node will broadcast the route request message to its neighbors and so on. During this process, while each node sends a route request message to its neighbors, it saves in its routing tables the source node, where the first request came. Once the route request message reaches the destination, the destination node replies with a unicast route reply message to the neighbor from which it first received the route request message. Hence, the route reply message travels back to the source, accordingly the source sends the packet to the destination [21]. Flooding-based routing techniques may be more appropriate for sparse nano-networks, i.e., low volume of nano-nodes at acceptable transmission range, as energy consumption is one of the main concerns in nano-networks.

Oukhatar et al. [3] proposed a probabilistic based broadcasting scheme for electromagnetic Wireless Nano-Sensors Networks (WNSNs) to reduce redundant retransmissions in flooding techniques, while AbuAli et al. [12] investigated the performance evaluation of the hierarchical AODV in electromagnetic nano-networks with the controlled flooding and CORONA. They evaluated the performance of these three protocols concerning energy consumption and network delay against transmission range and network density. Their performance evaluation showed that increasing the number of nano-nodes and their transmission range would result in increasing successful delivered packets (throughput), however increasing the number of nano-nodes and their transmission range would increase delay and energy consumption in CORONA and controlled flooding. This is due to the excessive broadcasting in these algorithms. On the other hand, hierarchical AODV consumes less energy than the other two protocols, as it suffers higher complexity and lower throughput.

Abushiba et al. [20] introduced a comparative analysis between AODV protocol and Dynamic Source Routing (DSR) protocol. The performance metrics in this study included packet loss, energy consumption, throughput, packet delivery and average end-to-end delay, while Xin et al. [21] studied the mechanisms of AODV and DSR, and they compared the Internet of Things (IoT) network with ad hoc network. They found that there are many similarities between both of them in the topology distribution as well as the node characteristics, hence with some modifications, it will be feasible to apply the routing protocols of wireless ad hoc network in the IoT and the Internet of Nano-Things (IoNT) paradigms.

Other examples presented in the literature for these adapted protocols are Deployable Routing System (DEROUS) and Multi-Hop Transmission Decision (MHTD). DEROUS was proposed for Software Defined Materials (SDMs) applications, and it is a routing scheme can be deployed on a static dense ad hoc nano-network topology with identical nano-nodes, where a certain nano-node in the center is elected to be the beacon node. This beacon node deploys different rings or sectors and assigns addresses to the surrounding nano-nodes located within its range, also it keeps periodically packets with all other nodes. Each nano-node sets the hop counts as the radius sector till the beacon. DEROUS affords a simple setup overhead and operates efficiently with lower packet retransmission rates [22].

MHTD is introduced by Pierobon et al. [5]. It is a routing framework for WNSNs used in a hierarchical architecture of nano-network, where a cluster head called nano-controller has more computing resources than the normal nano-nodes in the cluster. The objective of MHTD routing protocol is to optimize the use of the harvested energy, while increasing the overall network throughput. They also numerically evaluated the performance of this framework in terms of energy, capacity and delay with a comparison to the single-hop WNSN communication.

On the other hand, Mobile Ad hoc Network (MANET) is a kind of wireless ad hoc network, where devices are free to move randomly and organize themselves arbitrarily. So, their network topology may change rapidly and unpredictably, hence MANET can operate in a standalone way, or maybe connected to the Internet. Opportunistic Network (OppNet) is an extension of MANET, where devices move and communicate with each other freely through a wireless interface. Every node act as an independent router with no need for a central unit to control the network operations. OppNets face some constraints like no stable source to destination connection between the two nodes, so it depends on opportunities of connection between source and destination, moreover the location of a node is unknown, which makes the network topology variable for most of the times [23]. Moreover, OppNet faces intermittent connectivity and limited resources in terms of storage, bandwidth and power. Due to the intermittent connectivity, a direct path from source to destination is typically not given in any instance of time. Packets are delivered to the destination using hop-by-hop routing with a store-carry-forward technique [24]. The same perspective of communication in MANET and OppNet can be applied to nano-networks, in addition to the aforementioned restrictions of nano-nodes, which lead to the aim of introducing an appropriate routing scheme for such type of communication networks [25]. Stelzner et al. [26] provided an analysis of routing schemes and their requirements, which were acquired from the IoT to cope with the challenges of the IoNT because nano-networks share some characteristics of macro-scale MANET. They evaluated and compared MANET routing algorithms and analyzed their applicability for in-body nano-networks focused on the medical application scenarios.

2.4. Energy conservation routing protocols

The architecture of the Energy Conservation Routing (ECR) protocol consists of nano-interface, several nano-controllers and nano-nodes. ECR protocol uses a multilayer topology, where the division of layers is based on the single-hop transmission range of the nano-nodes, the distance from nano-nodes to the nano-interface and the width of each layer is one-half of the single-hop transmission range [11]. The main objective of ECR protocols is to minimize energy consumption in nano-networks. This category of routing protocols is specifically designed for self-powered nano-networks with a trade-off between complexity and design accuracy.

Afsana et al. [27] proposed an energy-efficient forwarding scheme for electromagnetic wireless nano-networks to improve the performance of nano-communication over the terahertz band for Wireless Body Sensor Networks (WBSNs) making it suitable for smart health applications. The channel behavior of the proposed scheme was studied taking into consideration the effect of molecular absorption, spreading loss, and shadowing. They stated that to allow continuous operation for nano-machines, the system requires energy harvesting. Their proposed scheme facilitates energy efficiency by selecting a multiple layered cluster-based multi-hop communication, which is supported by a nano-sensor energy model.

Whilst Al-Turjman [16] introduced a framework for data delivery in nano-networks called Enhanced Energy-Efficient Algorithm (E3A), where data is processed by nano-routers and then forwarded to a gateway connected to the Internet. E3A is a topology independent routing protocol, which deals with the randomness nature of nano-network topologies. In this routing scheme, the system determines the path from the nano-router to the destination node based on each nano-node's remaining energy.

2.5. Routing capability in SDN/NFV system

Our main approach aims at reducing the computational requirements of nano-nodes, besides decreasing the energy consumption and storage required to perform data routing among them. This can be achieved by virtualization of the routing network function by externalizing routing decisions from the actual nano-nodes, hence transferring the intelligence from nano-nodes to an external machine prepared to do the programmed scheme. This machine can perform the computations and calculations to manage different routes inside the nano-network domain, as a result providing a way to reduce the computations capabilities and power consumption from the nano-nodes themselves.

The interlock between SDN and NFV technologies is very famous in recent telecommunication systems. Likewise, this interlock plays a vital role in the virtual routing function for nano-networks. In our proposed computational architecture model for nano-networks [14], the SDN controller is considered to be a part of the Virtual Infrastructure Manager (VIM) of NFV architecture as illustrated in Figure 1, where all networking tasks are handled by the SDN controller. VIM is integrated with the SDN controller to manage both the physical and virtual network components of the Network Function Virtualization Infrastructure (NFVI).

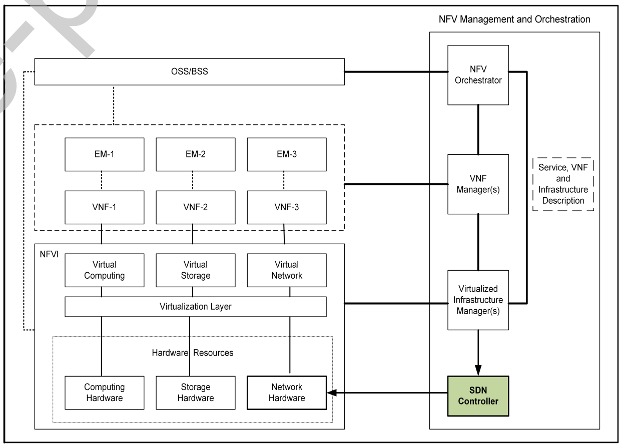

Figure 1: SDN interlock with NFV architectural framework [28].

The integration between SDN and NFV layers is mandatory in nano-networks since the NFV layer has complex networking requirements, which VIM only cannot provide such as the integration with traditional IP networks with different networking requirements, which require controlling both the virtual and physical network in the NFVI. The SDN controller manages the infrastructure domain, i.e., OpenFlow switches, smart micro/nano-gateways and nano-nodes, also it is responsible for detecting the packet-in received from the OpenFlow switch by processing the header of the packet to detect the destination address. Then, it sends a request to the corresponding VIM, which will be in contact with the VNF manager and NFV Orchestrator (NFVO) to obtain the corresponding path. A Routing Function Virtualization (RFV) machine, which is controlled by the VNF manger will find a path in its route table and sends a response back to the SDN controller. Once the SDN controller receives a response from VIM about the routing function, it sends a packet-out and pushes the corresponding entry to the flow table of the OpenFlow switch, which will update the micro/nano-gateway, accordingly the corresponding nano-router within the cluster of interest will forward the packet. Moreover, the SDN controller controls virtual and physical switches, and it provides the interconnection between different VNF containers. As part of network service definition on the NFVO, a service chain is required to implement any network function, this is called Service Function chaining (SFC). The required traffic forwarding is defined on the NFVO using VNF Forwarding Graphs (VNF-FGs), and it is implemented on the NFVI using the SDN controller [28]. Many vendors develop different products of VIMs, Virtual Network Function Managers (VNFMs) and NFVOs. OpenVIM, VMware and OpenStack are types of VIM. Cisco Elastic Services Controller (ESC), Ribbon and ONAP are examples of VNFMs, while Cisco Network Services Orchestrator (NSO) is an example of NFVO. Moreover, other vendors merge both VNFM and NFVO in one product like Tacker and Open Source MANO (OSM).

Batalle et al. [13] presented the analysis, design and implementation of the virtualized routing function. They described the design of the virtualized routing protocol enabling a simple management to avoid signaling messages overhead in the control plane level, also they described one of the first implementations of the functional NFV concept through the virtualization of the routing function over an OpenFlow network. Whilst Van Rossem et al. [29] demonstrated a basic mechanism enables an elastic service management by using an elastic router as an example. As all kinds of network services can be managed easily using NFV/SDN paradigm, they stated that a certain router can be offered as a service itself, i.e., Routing-as-a-Service (RaaS), and it can be deployed as a functional part of more advanced service.

While SDN/NFV system is a general framework that can be used with different types of infrastructure transforming the way of telecom service delivery, it can be used with nano-network to overcome its limitations and lead to faster development of profitable solutions. Galal et al. [14] proposed computational system architecture for nano-network communication with a layered approach combining SDN, NFV and IoT technologies. Their architecture is divided into five layers. The first is the nano-network layer, which represents the physical layer that comprises all physical devices and sensors. The second layer is the SDN layer, which is responsible for the intelligent delivery of data between devices. The third one called the IoT layer, which is responsible for data management and provisioning. The fourth layer is the fog computing layer, which is responsible for addressing and local computations. The fifth layer is the NFV layer, which is responsible for the global computations and decision-making process. They also proposed a set of functions and use cases showing their corresponding sequence diagrams, which describe a network demand in the nano-network paradigm. This system architecture has provided the possibility of managing and controlling a group of nano-nodes adding a substantial level of flexibility and reconfigurability for the futuristic nano-networks using the SDN/NFV technologies.

As long as nano-nodes have extremely weak processing capability, small memory units and very tiny batteries due to their nano-scale size, which requires an energy harvesting method to overcome the limited energy consumption with a tradeoff between energy harvesting and consumption. On top of that, the expected high density of nano-nodes in a nano-network causes a broadcast storm scenario, which leads to significant collisions in data transmission and reception [11]. Accordingly, SDN/NFV system will play this important role in data routing to externalize the complex computations from nano-nodes to decide what the best route is, where NFV layer is responsible for implementing a virtualized path discovery algorithm and selecting the best path to the destination instead of compiling these complex computations on nano-routers as will be illustrated later in Section 4.

2.6. Summary

Routing protocols play an important role in electromagnetic nano-network design and deployment. Hence, the implementation of suitable routing schemes is a key objective. With SDN and NFV technologies, nano-networks can overcome some of their constraints and limitations. Various research trials had been proposed in the literature. The summarized classification of data routing techniques in electromagnetic nano-network is illustrated in Figure 2.

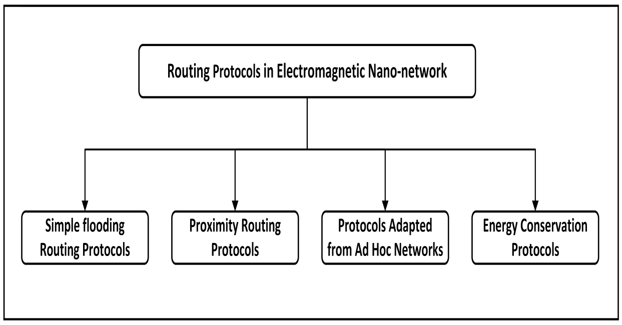

Figure 2: Classification of data routing in electromagnetic nano-network.

3. PROPOSED VIRTUAL ROUTING FUNCTION OF NANO-NETWORKS

In this section, we will propose a refinement of the computational architecture model of nano-networks and its components, which had been proposed in our previous work [14]. Then, we will illustrate the importance of data routing and clustering in nano-network context.

3.1. Nano-network computational architecture

Nano-network communication range in the terahertz band is expected to be between 10 nm and 100 nm, so the transmission range is extremely limited, which makes multi-hop routing a critical aspect. Moreover, the direction of a communication route is not deterministic, as it depends on the mobility of the nano-machine, which may lead to communication delays [16]. Based on our previous work in [14], and the presented work in [16], a hierarchical computational architecture is proposed for nano-network consisting of the following components:

- Nano-machines: They are the smallest and simplest nano-nodes. Because of their limited energy and communication capabilities, they can perform very simple tasks and can transmit data over very short distances. These nano-machines are composed of nano-sensors and nano-actuators, besides nano-communication units such as nano-memory, nano-antenna, nano-transceiver, nano-processor and nano-power unit [16] [30].
- Nano-routers: They are nano-nodes with higher computational capabilities and energy harvesting mechanisms rather than nano-machines. They can aggregate data coming to/from a set of nano-machines, and send it to their associate micro/nano-gateways defined later. Nano-routers can control the behavior of nano-machines by sending and/or receiving some functions such as ACTIVATE, DEACTIVATE, OPERATE, ACK, etc. [14]. These advanced capabilities will increase their size with more complexity in the corresponding fabrication and deployment features [16].
- Micro/nano-gateways: They are used to aggregate data coming to/from nano-routers and send the information to the micro-scale devices. Micro/nano-gateways are smart hybrid devices that can communicate in both nano-scale and classical communication paradigms in micro/macro-communication networks. The choice of micro/nano-gateway depends on the nature of the signal, the channel where the signal is propagated and the required task. The fabrication of these gateways is still an open research area, because the fabrication process has some challenges and requirements need to be satisfied from both sides of communication. From the nano-communication side, these gateways shall interact with different triggering and communication techniques related to nano-nodes to comply with them properly. So, they include a sensor part and a transduction part. The sensor part consists of a genetic cellular structure, that interacts with any triggering signal coming to/from nano-devices, e.g., changing temperature, light, color, frequency, ultrasound, magnetic or illumination fields, while the transduction part converts this sensed signal into electrical signal or stream of bits. This depends on the fabrication technology of nano-devices, besides the corresponding nano-network application [7]. From the other side, i.e., macro/micro-communication, these gateways have to speak any protocol that can communicate with the SDN/NFV system, e.g., OpenFlow protocol or P4 to enable the end-user to control and monitor the entire nano-network remotely over the Internet. Furthermore, the micro/nano-gateway has some knowledge of the nano-network routing topology based on its flow table, which is updated continuously by the SDN controller [16].
- SDN Switches: SDN enabled switches are used to aggregate and forward data coming to/from micro/nano-gateways according to the commands sent by the SDN controller by using OpenFlow signaling protocol in the southbound API. SDN switches represent the access layer, as they are responsible for the intelligent delivery of data between nano-devices [14]. Other signaling protocols can be used in the southbound API such as The Network Configuration (NetConf) protocol, Open vSwitch Database (OVSDB) management protocol, Simple Network Management Protocol (SNMP), Open Shortest Path First (OSPF) protocol, Multi-protocol Label Switching (MPLS), Border Gateway Protocol (BGP) and Intermediate System to Intermediate System (IS-IS) protocol [31].
- SDN Controller: SDN controller runs a network operating system. It can add, update and delete flow entries in the flow tables of SDN switches and micro/nano-gateways. Each flow table contains a set of flow entries; each flow entry consists of match fields, counters, and a set of instructions to be applied on the matching packets. There are many types of SDN controllers. They are depending on different aspects such as implemented programming language, performance metrics, the type of southbound interfaces they support and their support for distributed control or not. Example of SDN controllers are NOX, POX, ONOS, OpenDaylight, Ryu and Floodlight [32]. Hence, the SDN controller is the control plane of the SDN layer, while SDN switches and micro/nano-gateways are the forwarding/data plane.
- NFV Server: NFV server is the main controller of the system, where decisions, actions and computational calculations related to nano-nodes' functions will be computed on the external data center. Moreover, the NFV server is responsible for the best path calculations between the source nano-router and the destination nano-router, also it enables the clustering and the deployment of the virtual routing function of nano-networks, which will be illustrated later in this section. Hence, the NFV server represents the global computations [14].

For presentation clarity and consistency, we provide distinctions in Figure 3 for some terminologies used consistently in the proposed model, besides the rest of the paper. All devices/particles of nano-size are referred to nano-devices. The term nano-node is used to refer to a nano-machine and/or a nano-router, while nano-machine refers to nano-sensor and/or nano-actuators. The term micro/nano-gateway refers to the gateways, that represent the interface between micro and nano-communication paradigms. Figure 4 shows low-level diagram of the nano-network computational architecture model's components [14].

3.2. The role of routing in nano-networks

Routing is a challenge in nano-networks, as the major factor is the routing table growth. So, nano-nodes will not be able to

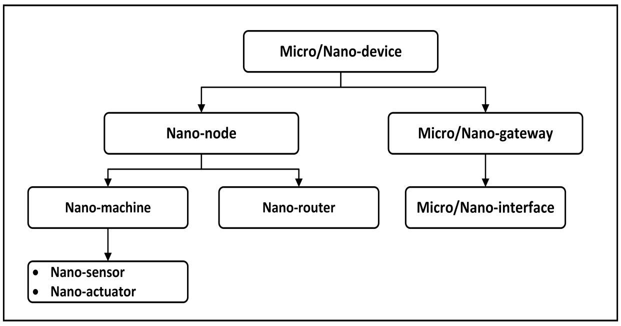

Figure 3: Distinctions in some recurrent terminologies used in the paper.

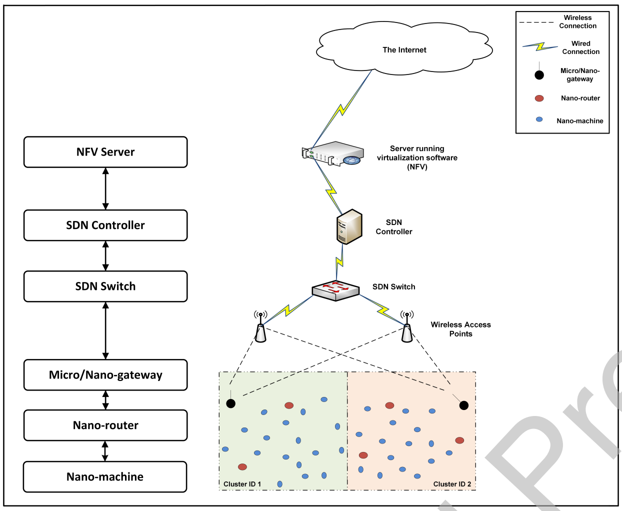

Figure 4: Low-level diagram of the nano-network computational architecture model's components [14].

handle different signaling messages such as route request and route reply, which are used in traditional IP networks, where routing tables are populated in routers to select the best path based on a certain metric, which is the Key Performance Indicator (KPI) of the system [33]. The most common metrics are hop-count, bandwidth, delay, reliability, load, cost, blocking probability and total number of packets. In the nano-network paradigm, two vital questions appear; if nano-networks need data routing, and if so, what is the purpose of routing in nano-networks. To the best of our knowledge, data routing in nano-networks is mandatory for two different processes, they are i) required action process and ii) packet delivery process.

3.2.1. *Required action process*

Based on the nano-network architecture model and the corresponding nano-network functions, which had been proposed in our previous work [14], data routing in nano-networks is obligatory in order to reach some probable unreachable nano-nodes from the micro/nano-gateway in order to forward different signals and/or functions like ACTIVATE, OPERATE and other proposed functions [14]. Due to the expected high mobility of nano-nodes in some applications, a nano-node may lose direct contact with the micro/nano-gateway. So, multi-hop forwarding between nano-routers will retrieve a full communication link between the nano-node and the micro/nano-gateway.

The action process is an order or command coming from the NFV controller, and it is required to be implemented by nano-nodes, or vice versa from nano-nodes to the NFV controller. When an order/command or a specific function has been received by the micro/nano-gateway, the function will be forwarded to a specific nano-node to be executed using the OPERATE function [14]. The forwarded message will be "*void* OPERATE *(execution-time, ID)*", and the corresponding ID will be nano-node's ID. In this case, the nano-node will be the definitive destination. In case of a specific order/function needs the participation of multiple nano-nodes, the micro/nano-gateway will request from other nano-nodes to give a hand in the process using a multicast or broadcast address.

Assigning a certain ID to a nano-node is not a simple task, because of the high scalability and complex synchronization between nano-nodes, so simple and feasible ways can be applied. For example, considering the hierarchical network architecture mentioned in Subsection 3.1, we can mark a nano-machine by both its corresponding nano-router and micro/nano-gateway to have different addresses. For example, an address like ($GW_2.NR_1.NM_4$) is used to refer to nano-machine number 4, within the domain of nano-router number 1, connected to micro/nano-gateway number 2 [34]. Furthermore, nano-nodes can be addressed by a group, where different nano-nodes can react in a certain way depending on the information that is being sensed. This information can be a triggering signal like change in temperature, light, ultrasound, magnetic field or illumination field [34]. Another example of addressing can be Radio Frequency Identification (RFID) tag with IPv6 address mapping. With a small nano-chip attached to the fabricated nano-antenna that is used for both receiving the reader signal and transmitting the tag ID. These tags are characterized by a unique identifier, and they can be applied to nano-nodes [14].

On the other hand, the location of nano-nodes during the operation has critical importance, that's why nano-nodes use LOCATE and ACK functions to identify their location and acknowledge the operation to the SDN/NFV system. LOCATE function is generated by the nano-node to send its location to the NFV controller, while ACK function is generated by the nano-node representing an acknowledgment message to the controller, hence nano-nodes can perform the right command in the right location [14]. In some routing protocols like CORONA, SLR, DEROUS, MHTD and ECR nano-nodes are aware of their location towards a reference point or anchor node. This depends on the nano-network application, while in other schemes like PBPD protocol, which will be proposed in Section 4, external resources can be used to guide nano-nodes to the targeted location. For example, in Body Area Network (BAN) external resources can come from magnetic, magneto-electric, optical and ultrasound devices, which are located outside the body can be used as a noninvasive method, which aids in the delivery of nano-nodes to a specific location or monitor their distribution [7].

3.2.2. Packet delivery process

The second process, that needs data routing in a nano-network is the packet delivery scenario. It is a normal packet delivery process between nano-nodes, where a nano-router will pass the packet to its neighbor, and this neighbor will pass it to another one and so on till the packet reaches the corresponding destination creating the best-routed path.

3.3. Clustering in nano-network

Nano-nodes can be associated with fixed geographic locations or mobile depending on the application. In order to provide an energy-efficient routing technique, network slicing or clustering concept has to be used in nano-networks. When the number of mobile nodes in a certain network increases, it causes rapid topology change and routing overheard, besides exchanging a large number of control messages. Therefore, a hierarchical structure is necessary to reduce this overhead. So, the network has to be divided into clusters, where the topology changes are harmonized internally, and the control messages are reduced. Hence, applying a clustering technique in nano-networks will help to reduce overhead computations and conserve the overall energy consumption by creating small topologies, i.e., sub-nano-network acting as an autonomous system. Nano-nodes in a certain cluster are classified based on their functionalities, i.e., nano-router is the cluster head, which is responsible for managing the cluster members, handling inter-cluster communication and data transmission. Micro/nano-gateway is used to forward data between different clusters. Any other node rather than nano-router and micro/nano-gateway is a cluster member node, which is a nano-machine. Accordingly, a cluster is an abstract grouping of nano-nodes, which may be created in an ad hoc manner or organized manner. The cluster is divided into a small number of cells (C), and the collection of nano-nodes inside each cell will be changed according to their mobility.

Clustering schemes are classified into different categories based on different aspects. Each scheme has certain objectives such as energy efficiency, mobility, stability, optimization or hybrid scheme [35]. In the nano-network paradigm, some parameters play a major role in cluster formation methodology such as the number of clusters and the number of nano-routers per cluster. In some applications, the numbers of clusters and nano-routers per cluster are predetermined. Another factor is nano-nodes mobility. Stable clusters are achieved when the deployed nano-nodes are static in nature. When the nodes are mobile, the membership of nano-nodes will be changed dynamically imposing clusters to change over time and need to be maintained continuously. Moreover, nano-nodes types and roles have an important impact on the cluster formation process. In some algorithms, cluster heads are randomly selected based on some criteria such as energy, connectivity or in a probabilistic manner. Therefore, algorithm complexity depends on the number of cluster heads, i.e., the number of nano-routers per cluster.

The clustering process into sub-nano-networks will be deployed using the NFV layer of the proposed computing architecture [14]. Each cluster contains at least one micro/nano-gateway, which has a full knowledge of the cluster topology. Smart micro/nano-gateway acts as the default gateway for any packets coming to/from nano-node inside the same cluster. Each cluster has a ”Cluster-ID”, which is attached to every route/packet advertised by micro/nano-gateway to/from nano-node inside the cluster. Each cluster acts as one separate broadcast domain, i.e., one multicast domain, where the cluster-ID is the broadcast ID. Each micro/nano-gateway has a cluster list that indicates the full knowledge of other clusters and other micro/nano-gateways in order to ease the communication between clusters and avoid routing loops. Micro/nano-gateway uses the predefined cluster list to check if the packet is communicating with the Internet or communicating with another cluster, accordingly the packet will leave the cluster to another one or the Internet. Nano-routers are responsible for data routing inside the same cluster, while micro/nano-gateways are responsible for data routing between different clusters and the Internet. Also, nano-routers are transmitting in both ways, i.e., to/from nano-machines and to/from micro/nano-gateways, as a consequence nano-routers have more powerful computing capabilities and energy harvesting mechanisms rather than normal nano-machines. Figure 5 shows nano-routers deployed in two-dimensional space occupied by a group of nano-machines in a square-shaped cluster, while Figure 6 shows a cube-shaped cluster. Hexagonal shape for a cluster can be an option like mobile cellular communication, because it covers an entire area without overlapping, i.e., it covers the entire geographical region without any gaps, however in nano-networks the communication over an extremely short distance in nano-scale. Implementation of different clustering techniques are suitable for the nano-network paradigm is still an open research area, which will be studied in our future work, so more cooperation between research communities is encouraged.

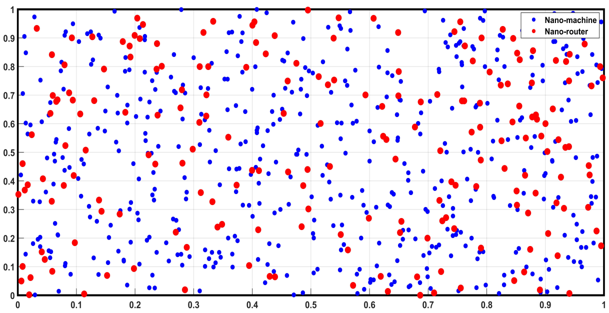

Figure 5: Two-dimensional cluster displays nano-machines and nano-routers in randomized deployment.

4. PROPOSED PATH DISCOVERY PROTOCOL FOR ELECTROMAGNETIC NANO-NETWORKS

It is worth pointing out that one of the most attractive applications of nano-networks is IoNT in BAN, where nano-devices

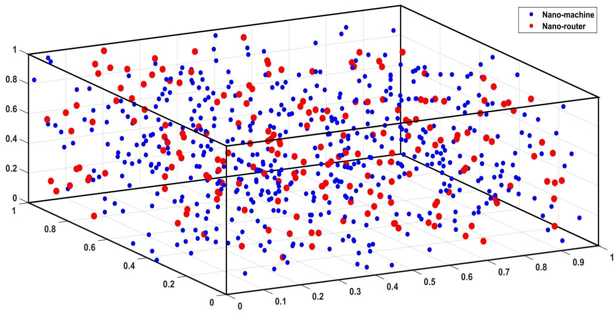

Figure 6: Three-dimensional cluster displays nano-machines and nano-routers in randomized deployment.

are injected into the human body to monitor the body measurements and pass it to a data center for processing and computing. Temperature, pressure, heartbeats, vibration, glucose levels, etc. are types of these measurements. Furthermore, nanorobots inside the biological tissues can detect and eliminate malicious viruses or cancer cells, hence making the treatment less invasive and real-time [16]. When a set of nano-machines/nanosensors are injected altogether with a group of nano-routers into a dynamic environment like the human body, all nano-devices can move freely to different locations. However, nano-sensors cannot communicate usually with each other because of their limited capabilities, so passing the sensed data/information to a nano-router, which has higher energy storage and powerful processing capabilities will be the option for data forwarding. The nano-router collects data and forwards it to a micro/nanogateway, which is connected to an external SDN switch and SDN controller followed by an NFV server forming external SDN/NFV computing architecture. This computing system usually connects to the Internet to allow remote monitoring and processing.

In this section, we will propose the PBPD scheme for electromagnetic nano-networks by presenting the model definition and the operation definition of the algorithm considering the use case of the IoNT in BAN as a reference scenario. This algorithm uses the probability of nano-routers' existence as a metric to select the best path to the destination.

4.1. Model definition

As nano-nodes cannot handle partial or full routing tables, the routing technique has to be simple with low computations and low energy consumption. The proposed path discovery protocol is introduced based on the computational architecture for nano-networks, which had been proposed in [14]. This protocol uses a hierarchical cluster-based architecture that extends the network operation complexity from the individual nanomachines towards SDN/NFV system. This will shift the processing complexity from nano-nodes and reduce their power consumption. The proposed probability-based path discovery protocol uses the probability of nano-routers' existence as a routing metric for the next-hop selection. This scheme is based on the probability of nano-routers' density surrounded by a group of nano-machines, which are located inside a certain cell. The selection of the next-hop cell is based on the highest existence probability of nano-routers. This procedure allows us to initiate a multi-hop communication, where there is a sufficient probability of nano-routers' existence, which will increase the overall throughput of the nano-network. The main idea is to use the probability information to discover and select the best path between a source nano-router and a destination nano-router. The higher the probability of nano-routers' existence, the higher the probability of successful transmission.

4.2. Operation definition

The operation process of the proposed protocol is a combination of four phases namely Topology Detection Phase, Probability Distribution Phase, Decision Phase and Data Forwarding Phase as shown in the illustrated flowchart in Figure 7. Firstly, in the topology detection phase, the strategy is based on how the nano-nodes maintain topology information. As nano-nodes do not have sufficient memory to store such information, an external system will be responsible for topology detection and density exposure for mobile nano-nodes, which form the transient nano-network topology. For instance, to track the density and mobility of nano-nodes inside the human body, a potential strategy to scan the area of interest is Computed Tomography (CT), which uses computer-processed combinations of X-ray measurements taken from different angles to produce cross-sectional images/slices for a specific area of a scanned object allowing the processing console connected to MRI to track and record the location of the mobile nano-machines and nano-routers. Hence, forming a temporary network topology for nano-network, which is the preliminary step in the topology detection phase as shown in the schematic representation for the operation in BAN in Figure 8. It is worth mentioning that CT and MRI scan can enhance precision in some applications, however, it is a primeval method suitable for in-person medical perambulate. Moreover, it not affordable in all cases, because of their size, and the frequent hospital visits. So, more research has to be done in this area to simplify this operation and to figure out other tools to scan the area of interest and check the transient topology of the nano-network. Smart gloves scanner or smart clothing and textile with attached biometric sensors could replace MRI.

Secondly, in the probability distribution phase, the path discovery algorithm will calculate the probability of having nanorouters inside each cell, e.g., density calculation per cell, taking into consideration that cross-sectional area of both clusters and cells are predefined and constant during the operation. Thirdly, in the decision phase, predicted paths are evaluated by selecting the cells, which have the highest probability distribution of nano-routers with the promotion of the best path between the source nano-router and destination nano-router. Lastly, data forwarding phase is accomplished by forwarding the packet from the sender nano-router to a certain nano-router inside the next cell, which has a high probability of nano-routers' existence. As some of nano-routers inside the recipient cell have no direct line-of-sight with the sender nano-router, so the forwarding path is predetermined before the forwarding process based on the following conditions:

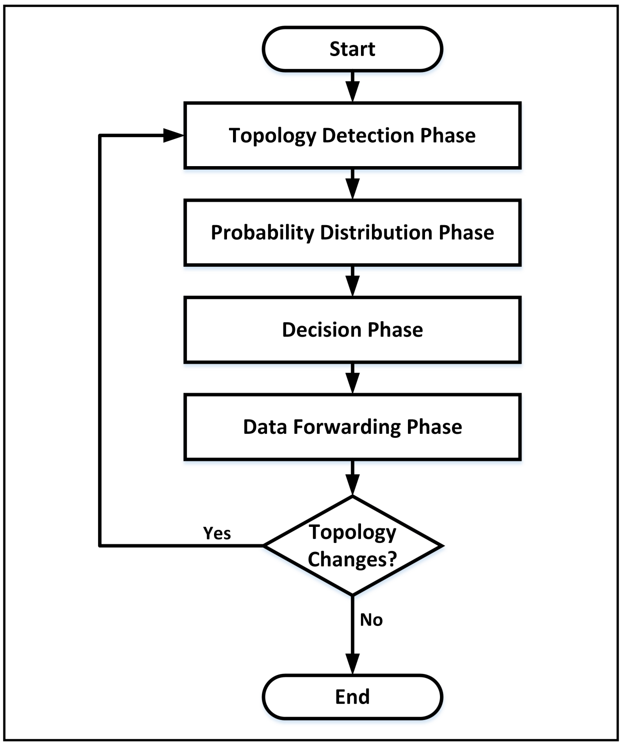

Figure 7: Flowchart represents the general structure of the methodology used by PBPD protocol.

- There is a line-of-sight between both nano-routers, i.e., sender and recipient.
- The recipient nano-router must belong to a cell that participates in a path leading to high successful end-to-end transmission, i.e., a path has a high probability of nano-router existence to the destination.
- The next-hop nano-router has to meet both previous conditions with his consecutive hop.

After the transient topology changes, the four phases of PBPD protocol will be repeated. This protocol with its four phases is externalized on the NFV layer as illustrated in Section 3. This prototype has been proposed based on some assumptions and hypotheses listed as follows:

- All nano-nodes fulfill the minimum energy, memory and computational requirements.
$$NR \in (E_{\mathrm{NR_{min}}}, Mem_{\mathrm{NR_{min}}}, CPU_{\mathrm{NR_{min}}})$$
$$NM \in (E_{\mathrm{NM_{min}}}, Mem_{\mathrm{NM_{min}}}, CPU_{\mathrm{NM_{min}}})$$
- All nano-nodes are identified by a specific address or ID.
$$NR \in (ID)$$
$$NM \in (ID)$$
- The total number of injected nano-routers and nano-machines inside a specific area of interest are predefined and constant during the process [14].

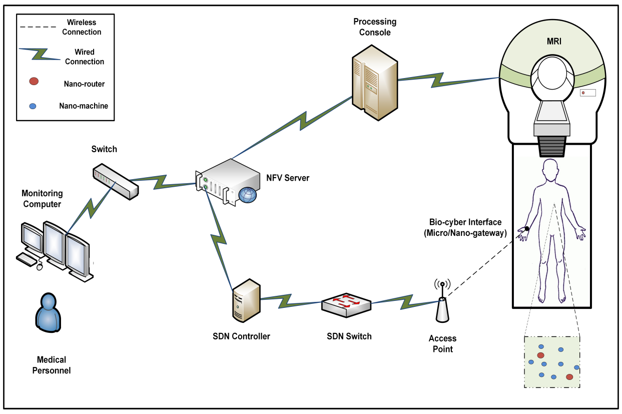

Figure 8: Schematic representation for BAN.

$$NR_{\mathrm{number}} = Constant$$
$$NM_{\mathrm{number}} = Constant$$

- All cells inside a cluster are of equal volume.
$$C_{1_{\mathrm{volume}}} = C_{2_{\mathrm{volume}}} = C_{\mathrm{i}_{\mathrm{volume}}}$$
- The cluster cross sectional area and the cell cross sectional area are predefined and constants during the process.
$$Cell_{\mathrm{Area}} = S = Constant$$
$$Cluster_{\mathrm{Area}} = Constant$$
- The nano-router topology is not deterministic, and it changes periodically, due to the mobility and density of nano-routers.
$$T_{\mathrm{TPG}} \Rightarrow \rho$$
- The information related to the probability distribution is updated regularly to the controller based on nano-routers' mobility and density.
$$P(S) \propto \rho$$
- Successful end-to-end transmission cannot be assured, while high probability values of successful transmission can be guaranteed.
$$0 \leqslant P(S) < 1$$

5. ANALYTICAL MODEL OF THE PROPOSED SCHEME

In this section, we will propose the analytical model of the PBPD scheme for electromagnetic nano-networks by illustrating the nano-routers deployment model, the energy consumption model and the time allocation model. Table 1 illustrates the frequently used parameters in the analytical model with their corresponding definitions.

5.1. Nano-routers deployment model

Deployment and injecting nano-networks inside a living biological environment present challenges in many different research fields such as signal propagation, extremely high

Table 1: Table of the frequently used parameters

Parameter	Definition
K	Number of nano-routers inside a specific cell.
λ	Poisson distribution parameter.
$P(K)$	Probability of having (K) nano-routers inside a specific cell.
ρ	Nano-routers' density per unit area.
S	Cell area.
N	Total number of injected nano-routers inside a specific cluster.
$P(S)$	Probability of successful end-to-end transmission over a certain path.
C	Total number of cells inside a certain cluster.
i	Cell index inside a specific cluster.
E_{NM}	Total energy consumption of a single nano-machine.
G	Cost function of the consumed energy.
T	Total number of transmitted packets.
E_{TX}	Energy consumption to transmit one packet.
R	Total number of received packets.
E_{RX}	Energy consumption to receive one packet.
N_{bits}	The packet length/size.
W	The coding weight.
$E_{\text{Pulse-TX}}$	The energy consumption to transmit a pulse.
$E_{\text{Pulse-RX}}$	The energy consumption to receive a pulse.
E_{NR}	Total energy consumption of a single nano-router.
Ag	Total number of aggregated packets.
E_{Ag}	Energy consumption to aggregate one packet.
Pr	Total number of processed packets.
E_{Pr}	Energy consumption to process one packet.
E_{PTH}	Total energy consumption over a certain path.
N_{PTH}	Total number of nano-routers over a certain path.
$P_{\text{EC}}(K)$	The probability of energy consumption of (K) nano-routers.
T_{TPG}	The lifetime of a nano-network topology.
T_{PROC}	The total time for a certain nano-network process.
T_{RT}	Routing decision and computation time inside the NFV layer.
T_{SUB}	Submission time for a certain function from the NFV layer to the nano-network layer.
T_{EXEC}	Execution time for a certain function within the area of interest.
T_{ACK}	The time to send an acknowledgment from the nano-network layer up to the NFV layer.

electromagnetic frequencies required for communication between nano-nodes, besides the channel in biological tissues has high path loss and absorption noise. Broadly stated, injected nano-nodes will be carried by the blood circulatory system, and all of them will flow through the veins of the body. Moreover, nano-nodes must be encapsulated in a biocompatible capsules or artificial cells before being implanted into the human body to avoid any problems in case they are drafted to any unintended locations [36]. To the best of our knowledge, the deployment strategies remain scarcely explored in the literature. For instance, Canovas-Carrasco et al. [36] studied a human hand scenario given the thinness of its biological tissues. They proposed an architecture where nano-machines circulating in the bloodstream, collecting and exchanging information with a nano-router implanted into the skin of the hand. They also provided a study for radio propagation with the path loss in the human hand to properly design a communication scheme for a BAN.

The distribution process of grouped nano-routers inside a certain cell can be represented by a Bernoulli trial (binomial trial), where the nano-router has a probability of success (existence) and probability of failure (nonexistence), which is equivalent to one minus the probability of existence. In probability theory, this can be represented by a binomial distribution. When the number of trails is very large tends to hundreds, thousands or millions, and the probability is unknown or very low. This leads the binomial distribution to be approximated to the Poisson distribution [37].

On the other hand, in statistics and probability theory, a point process is a collection of points randomly located on a certain underlying space such as line, cartesian plane or any abstracted volume. A point process can be used as a mathematical model of phenomena or objects representable as points in a space. Besides, a Poisson process is a memoryless stochastic point process, where an event has just occurred or that an event hasn't occurred in a long time giving no clue about the likelihood that another event will occur soon. Memoryless property means the history of a certain random variable that is distributed exponentially plays no role in predicting its future. So, a Poisson process is a stochastic point process, where nano-routers' density is exponentially distributed [38].

Hence, Poisson distribution is the most suitable approximation for our model, because of the following reasons:

- The expected massive number of nano-nodes crossing the area of interest (thousands or millions).
- The probability of finding any nano-router inside a certain cell is very small or unknown.
- Poisson approximation is more accurate to represent the high mobility particles crossing a certain cross-sectional area in a certain time frame.
- The events of finding nano-router at any two cells are independent.
- Poisson process is a memoryless stochastic point process. So, what happens in the system depends only on the present time, i.e., the position of each nano-router is independent of the position of other nano-routers, because we do not know anything about the history of events up until that point.

Accordingly, nano-routers are distributed in the space according to homogeneous Poisson distribution process with parameter λ. So, the probability of having (K) nano-routers inside a specific cell is presented by (1)

$$P(K) = \frac{\lambda^K e^{-\lambda}}{K!} \tag{1}$$

Where λ represents Poisson distribution parameter equals to nano-routers' density (ρ) per cell area (S) [5]. Accordingly:

$$P(K) = \frac{[\rho S]^K e^{-[\rho S]}}{K!} \quad (2)$$

Where $K = 0, 1, 2, ..., N$

From (2), it is deduced that the probability of having zero nano-routers inside a specific cell, i.e., $P(K = 0)$ is present in (3).

$$P(K = 0) = e^{-[\rho S]} \quad (3)$$

Accordingly, the probability of having at least one nano-router inside a specific cell equals to $P(K \neq 0)$ as presented in (4)

$$P(K \neq 0) = 1 - e^{-[\rho S]} \quad (4)$$

Usually, there are multiple paths between the source nano-router and the destination nano-router. Each path has a different routing probability of successful end-to-end transmission. As the routing metric is the highest probability of having nano-routers inside a specific cell, the shortest path may not be elected as the best route to the destination, despite having minimum hop counts. In this case, the shortest path may have a low probability of successful end-to-end transmission rather than the long one, which may have more hop counts with a higher probability of successful end-to-end transmission. This indicates that the density of nano-routers inside the cells, which form the long path is higher than the shortest one. Accordingly, the probability of successful end-to-end transmission over a certain path $P(S)$ is calculated by the multiplication of all nano-routers' existence probabilities along this path as presented in (5).

$$P(S) = \prod_{i=1}^{C} P_i(K) \quad (5)$$

Where $i = 1, 2, ..., C$

5.2. Energy consumption model

Energy consumption in nano-nodes is one of the most important factors that affect nano-network applications. Authors in [16] stated that most of the energy consumption at the nano-machine is used by data communication during transmission and reception. So, the total energy consumption of a nano-machine is represented as in (6).

$$E_{NM} = G(T * E_{TX} + R * E_{RX}) \quad (6)$$

Where (G) represents cost function of the consumed energy. (T) and (R) represent the total number of transmitted and received packets respectively. (E_{TX}) and (E_{RX}) represent the energy consumption to transmit and receive one packet respectively.

Authors in [39] quantified the energy consumed in the transmission and in the reception of a packet (E_{TX}) and (E_{RX}) as represented in (7) and (8) respectively.

$$E_{TX} = N_{bits} * W * E_{Pulse\text{-}TX} \quad (7)$$

$$E_{RX} = N_{bits} * W * E_{Pulse\text{-}RX} \quad (8)$$

Where (N_{bits}) represents the packet length or size and (W) represents the coding weight or the probability of transmitting a pulse (1) instead of transmitting a pulse (0). ($E_{Pulse\text{-}TX}$) represents the energy consumption for the transmission of a pulse, and ($E_{Pulse\text{-}RX}$) represents the energy consumption for the reception of a pulse. Based on the numerical results in [39], the average number of ones and zeros in a packet is balanced, so (W) equals 0.5, ($E_{Pulse\text{-}TX}$) equals 1 PJ and ($E_{Pulse\text{-}RX}$) equals 0.1 PJ.

As discussed in Section 3, the major function of the nano-router is data aggregation and routing of the received packets from different nano-machines. As a result, the capabilities of a nano-router are higher than that of a nano-machine, therefore it is expected to consume more energy than nano-machine. Besides the energy consumption during data transmission and reception, nano-routers consume additional energy during data aggregation and processing overhead. On the other hand, the energy consumption coming from control packets will be saved, thanks to the SDN/NFV system, that decouples the routing intelligence from nano-routers and move it externally. Equation (9) represents the total energy consumption of a single nano-router [16].

$$E_{NR} = G(T * E_{TX} + R * E_{RX}) + G(Ag * E_{Ag}) + G(Pr * E_{Pr}) \quad (9)$$

Where (Ag) and (Pr) represent the total number of aggregated and processed packets respectively. (E_{Ag}) and (E_{Pr}) represent the energy consumption to aggregate and process one packet respectively.

From (6) in (9), the total energy consumption in a nano-router can be expressed in terms of the total energy consumption of a nano-machine as presented in (10).

$$E_{NR} = E_{NM} + G(Ag * E_{Ag} + Pr * E_{Pr}) \quad (10)$$

Accordingly, the total energy consumption over a certain path can be calculated as shown in (11)

$$E_{PTH} = N_{PTH} * E_{NR} \quad (11)$$

Where N_{PTH} is the total number of nano-routers over a certain path. The probability of energy consumption of (K) nano-routers can be represented by the Poisson distribution process with parameter λ equals $[\rho S]$ with a mean and variance are equal to λ. So, $P_{EC}(K)$ can be represented as shown in (12).

$$P_{EC}(K) = 1 - e^{-[\rho S]} \quad (12)$$

5.3. Time allocation model

Concerning mobile nano-nodes, it is obvious that their locations are always changing among different cells/clusters. Nano-nodes can move easily between different cells inside the same cluster, or they can depart to different clusters. This causes regular changes in their neighboring nano-nodes, as a result, a rapid change in the corresponding nano-network topology.

This indicates that each nano-network has a certain transient topology with a specific lifetime. T_{TPG} is defined as the time interval, in which the topology of a nano-network has the same participants nano-nodes (nano-machines and nano-routers), i.e., the time, in which the topology has not been changed. Equation (13) characterizes the total required time interval for a certain nano-network process to be implemented starting from the nano-network layer up to the NFV layer.

$$T_{\mathrm{PROC}} = T_{\mathrm{RT}} + T_{\mathrm{SUB}} + T_{\mathrm{EXEC}} + T_{\mathrm{ACK}} \tag{13}$$

Where T_{RT} represents the total time needed for different computations inside the NFV layer, besides taking the corresponding routing decisions. T_{SUB} represents the time required to submit/send a specific function/order from the NFV layer to the nano-network layer, T_{EXEC} represents the execution time for a certain function and T_{ACK} represents the required time to send an acknowledgment from the nano-network layer up to the NFV layer. T_{RT} depends on the instantiation/embedding time of the routing service chaining inside the NFV ecosystem, while T_{EXEC} depends on the speed of the nano-processor clock cycle and its attached nano-memory. T_{SUB} and T_{ACK} are propagation delays through the wireless media. Their values depend on the use case/application of a real nano-network. In BAN, for example, the propagation delay is the time needed by a bit to propagate inside the human body from a nano-node towards the micro/nano-gateway and outside the human body from the micro/nano-gateway to the high-performance computing center running the SDN/NFV system.

As long as the nano-network topology changes, the routing paths are changed frequently, and the expected corresponding outcomes will be changed accordingly. Hence, to guarantee accurate results from a potential nano-network, all the required computations, routing decisions and functions execution have to be carried out and completed during the topology lifetime (T_{TPG}) and before its expiration. So, the total time to complete a certain nano-network's process (T_{PROC}) must be less than or equal to the nano-network topology lifetime as indicated in (12) and illustrated in Figure 9. As a result, each topology snapshot appears as a static frame represents the distribution of nano-nodes at a certain time, while the continuous sequence of snapshots/frames for the nano-network topology because of the mobility of nano-nodes makes the overall system appears as a dynamic system. It is worth mentioning that the minimum time for a frame/topology depends on the speed of nano-nodes in a specific area of interest. For example, if they are injected into the human body, they will follow the blood circulation velocity. While if they are injected into air, they will follow the speed of the wind.

$$T_{\mathrm{PROC}} \leqslant T_{\mathrm{TPG}} \tag{14}$$

6. PERFORMANCE EVALUATION OF THE PROPOSED SCHEME

Performance analysis is very important in the design of nano-networks, because it provides the flexibility to adjust various

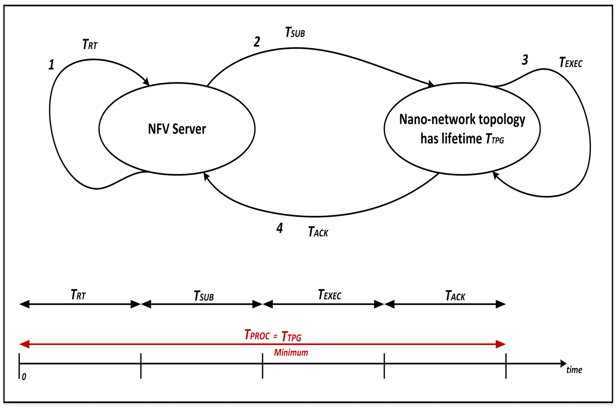

Figure 9: Handshake diagram for time allocation model.

parameters in the planning phase before the operational phase. In general, there are three basic techniques for performance evaluation of any telecommunication network. They are measurement, analytic modeling and simulation [40]. Measurement is the most fundamental approach, and it may be achieved in hardware, software or in a hybrid technique. Analytic modeling provides developing a mathematical model of the network, while the simulation technique involves designing a model that represents a real system in certain important aspects. Of the three methods, we will focus in this paper on the performance evaluation of the analytic modeling.

In this section, the overall performance of the PBPD protocol for nano-networks has been evaluated analytically in terms of performance metrics; energy consumption and successful end-to-end transmission, followed by a qualitative comparison between PBPD protocol and other routing schemes proposed in the literature.

6.1. Analytic modeling

The simulation had been performed using MATLAB, where nano-nodes are randomly distributed within the simulation area, which is a square of (1 mm * 1 mm) includes 100 nano-routers and 500 nano-machines. Our focus is on nano-routers' topology, as they are responsible for data routing. The topology was formed using a weighted random geometric graph, where the weights represent different delay values of the communication channel between nano-routers. Figure 10 shows the generated random graph between 100 nano-routers and 500 nano-machines highlighting the network topology of the nano-routers only for more clarity. The value associated with each nano-router represents the nano-router ID, they are numbered from 1 to 100. From the total randomized distributed 100 nano-router, we have selected two random nano-routers, one represents a source nano-router, and the other one represents a destination nano-router. All the possible paths between these source and destination nano-routers across the random geometric graph have been computed, then all cells participated in each path have been defined, hence the probability density of having at least one nano-routers inside each participated cell has been calculated as per equation (4). Accordingly, the probability of successful end-to-end transmission for all paths has been calculated as per equation (5), besides the total end-to-end delay (weight) for each path, which equals to the sum of all delay values (weights) across that path. Then, the path with the highest probability of successful end-to-end transmission has been elected, besides the path with minimum weight (i.e., minimum delay).

Figure 11 shows two paths between two nano-routers were selected randomly, the source nano-router (NR 60) and the destination nano-router (NR 70). The green path represents the highest probability of end-to-end successful transmission based on nano-routers' density (NR 60, NR 77, NR 98, NR 3, NR 76, NR 44, NR 52, NR 70), while the red path represents the path with minimum weight (NR 60, NR 63, NR 56, NR 81, NR 69, NR 97, NR 55, NR 70). We can deduce that the path with the highest probability of end-to-end successful transmission will be used in the transmission, despite having higher delay (weight) value. This is because the high density of nano-routers participated in the transmission process, which provides more possibility of successful transmission to the destination nano-router rather than the minimum delay path, which has a low probability of end-to-end successful transmission. The proposed algorithm of the PBPD protocol is illustrated in algorithm 1.

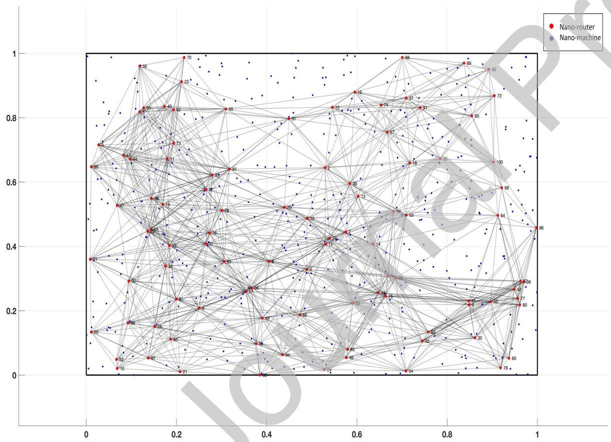

Figure 10: Generated random network topology of nano-routers.

Figure 12 shows the probability of having at least one nano-router inside a specific cell. It is obvious that as the total number of nano-routers inside a specific cell increases, the probability of having at least one nano-router inside a cell will be increased. Besides, Figure 13 shows the probability of end-to-end successful transmission over a certain path. It is obvious that for a certain number of nano-routers inside the cell, as the total number of cells participating in the transmission across the path increases, the probability of successful end-to-end transmission will be decreases and vice versa. For example, if the total number of nano-routers inside a cell equals four, using a path that includes only two participated cells to the destination

Algorithm 1 Probability-based path discovery scheme

Inputs:
- Total number of nano-routers.
- Total number of nano-machines.
- Source nano-router ID.
- Destination nano-router ID.

Outputs:
- Highest successful end-to-end transmission path.
- Minimum delay path.

```
Scatter all nano-nodes within the area of interest.
Create random network graph between all nano-nodes and assign random weights (delay values).
Calculate all possible paths between source nano-router and destination nano-router "A".
for "A" do
Calculate the path with minimum delay "a".
Determine the number of cells participated in any path.
Determine the total number of nano-routers inside each cell.
Calculate the probability of having at least one nano-router inside each cell.
Calculate the probability of successful end-to-end transmission.
if more than path have equal highest successful end-to-end transmission probability then
    Elect the path with the lowest delay.
else
    Calculate the maximum probability of successful end-to-end transmission "b".
    return "a".
    return "b".
end if
end for
```

is better than using a path that includes five cells to the destination and vice versa. This means that there is a trade-off between the total number of cells participated in a path and the probability of successful end-to-end transmission for a certain number of nano-routers inside cells. Moreover, as the total number of nano-routers inside a certain cell increases, the probability of total energy consumption will be increased exponentially as illustrated in Figure 14, accordingly the probability of total energy consumption across the path between the source and destination nano-routers will be increased.

Furthermore, it is obvious that if the total number of nano-routers inside a certain cell becomes greater than five, the probability of successful end-to-end transmission will be nearly constant, i.e., the system will have almost the same routing efficiency and probability of successful end-to-end transmission compared to the case of using more than five nano-routers inside the cell. Consequently, it is better to use a small number of nano-routers during the injection process to decrease the total cost and the total energy consumption inside the cell, while maintaining a very high probability of successful transmission.

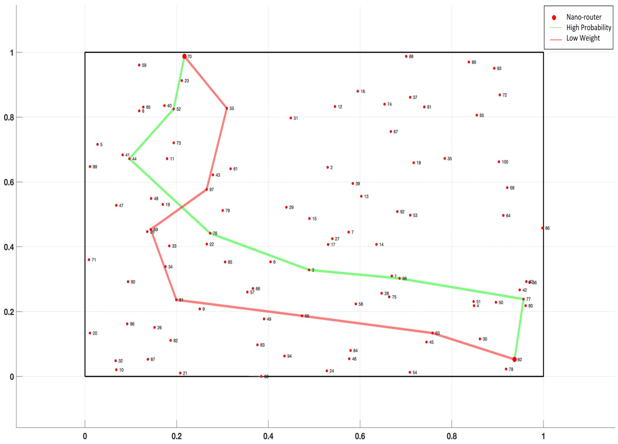

Figure 11: Highest probability path in green and lowest weight (delay) path in red between two random nano-routers.

As a result, the main area of interest has bounded by a lower threshold of three nano-routers and an upper threshold of five nano-routers inside the cell. This recommended range will provide a very high probability of successful transmission/routing efficiency (higher than 90%), while maintaining lower cost and lower overall energy consumption of nano-routers.

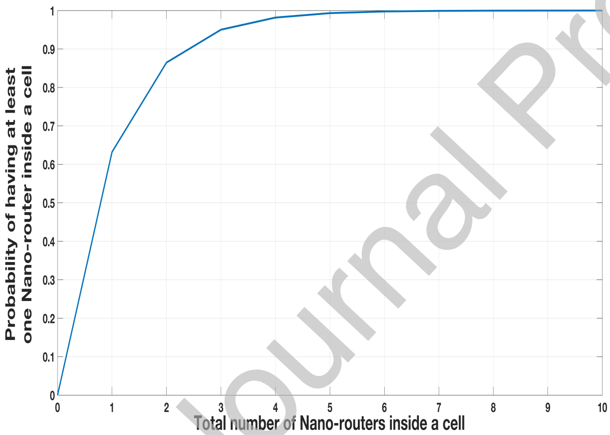

Figure 12: Probability of having at least one nano-router inside a specific cell.

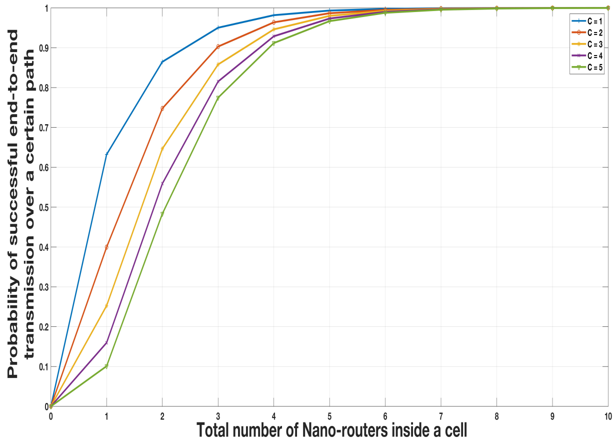

Figure 13: Probability of end-to-end successful transmission over a certain path.

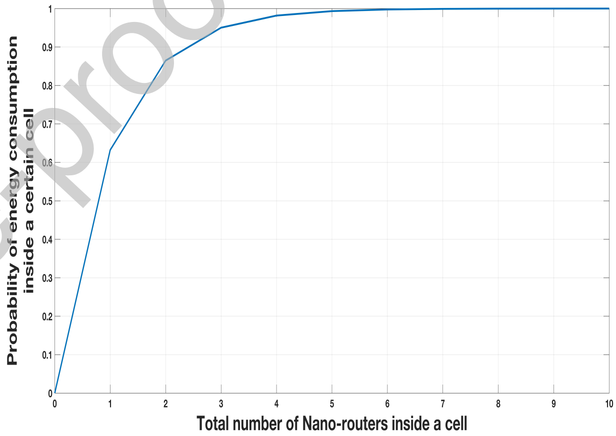

Figure 14: Probability of energy consumption inside a certain cell.

6.2. Qualitative comparison

Table 2 summarizes the comparison between our proposed PBPD protocol with some of the routing protocols proposed in the literature. We choose CORONA and SLR from the classification of proximity routing protocols. AODV, DEROUS, and MHTD from the protocols adapted from ad hoc networks, while ECR is chosen from energy conservation protocols. The evaluation and comparison had been achieved based on the following criteria:

- Network Structure: Electromagnetic nano-network structure can be classified as a flat structure or hierarchical structure. Flat structure, where all nano-devices have the same role or task, e.g., the source nano-device sends a packet to a neighbor nano-device, then this neighbor forwards the packet to its neighbor and so on till the destination. Examples of routing protocols designed based on the flat structure are CORONA, SLR, AODV and DEROUS. Hierarchical structure, where nano-devices are classified hierarchically with different roles and functions for each class, e.g., nano-machine, nano-router, micro/nano-gateway [11]. Examples of routing protocols designed based on hierarchical networks are MHTD, ECR and PBPD.

- Routing Path: Electromagnetic nano-network can be classified as single-path or Multi-path protocols. Single-path protocol, when each nano-node receives or generates a packet, it forwards it to a specific next-hop. This type of protocol can reduce energy consumption, however they increase the possibility of packet loss and transmission delay, in case of any node failure along the path. Examples of single-path protocols are MHTD, ECR and PBPD. Multi-path protocols are flood-based when a nano-node receives or generates a packet, it needs to decide whether to forward or drop it, based on certain computations/calculations. Usually, these protocols need lightweight computing resources, but this will increase the energy consumption of the node. Examples of multi-path protocols are CORONA, SLR, AODV and DEROUS [11].

- Position Awareness: Nano-nodes that have position information can control the transmission in a better way by limiting the flooding area. In CORONA and SLR, nano-nodes are aware of their hop counts to the anchor nodes. Also, in DEROUS and MHTD, nano-nodes are aware of their hop counts from the beacon node and the nano-controller respectively. While in ECR protocol, nano-nodes are aware of which layer they belong to. PBPD protocol doesn't depend on a distance towards a certain reference point, it uses the density of nano-routers to define the best path.
- Node Deployment: Node deployment can be deterministic or random. This affects the performance of the routing protocol. In deterministic scenarios, routing paths can be predefined by placing the nodes manually such as CORONA, SLR and DEROUS protocols. While in a random scenario, which is the most deployment method used in nano-network applications, the nano-nodes form their network in an ad hoc manner such as AODV, MHTD, ECR and PBPD protocols.
- Node Mobility: Nano-network protocols can be classified based on nano-nodes' mobility to static protocols or mobile/dynamic protocols. Static protocols, when nano-nodes have fixed position. As a result, the routing path can be predetermined in the initial phase and can be updated easily during the transmission time. Examples are CORONA, SLR and DEROUS protocols. While in mobile protocols, nano-nodes are moving during the operation. Examples are AODV, MHTD, ECR and PBPD protocols.
- Energy Consumption: Routing protocols need to consider the energy consumption of nano-nodes. In hierarchical routing protocols, the energy consumption of a nano-node is always less than the case of flat structure protocols. Because in hierarchical structure, nano-machines will be responsible for sensing and actuating, nano-routers will be responsible for data aggregation and forwarding, while micro/nano-controllers will be responsible for interacting with other systems or the Internet. Hence, the distribution of tasks will decrease the energy consumption inside the node.
- Computational Complexity (Simplicity): The less computations/calculations nano-nodes need to perform, the higher the simplicity of a routing protocol. In CORONA or SLR protocols, nano-nodes need to compare their coordinates with the coordinates in the received data packet, therefore their complexity is slightly higher than PBPD protocol, where nano-nodes do not need to perform local computations and/or calculations, thanks to the externalized SDN/NFV system, which takes care of this calculations.
- Scalability: Routing protocols can work efficiently with the increasing workload (number of nodes). In general, the hierarchical routing protocols have good scalability comparing to proximity routing protocols like CORONA or SLR, where the scalability drops, because of the increased flooding schemes caused by high number of nodes.

7. CONCLUSION AND FUTURE WORK

Data routing in nano-networks faces unique challenges based on several factors such as the scale size of nano-nodes, which leads to limited computing capabilities and power consumption. So, nano-nodes will not be able to store routing tables or perform routes lookup. Furthermore, the expected scalability issues of nano-network, which may contain thousands or millions of nano-nodes acting as the main infrastructure for the IoNT. Moreover, the expected high mobility of nano-nodes in different applications like environmental applications, where nano-machines will be scattered into the air to collect some environmental measurements. They will be moved by the wind, so changing their location, controller allocation and link quality. Similarly, in medical applications, where BAN is one of the most popular examples of the dynamic nano-network implementation. When a group of nano-nodes are injected into the human body to monitor/track the body measurements, they will be affected by the blood circulation velocity, in addition to molecular absorption noise, which will affect the link communication, quality, speed and location. All of these factors make an efficient data routing technique for nano-network induces very low computational complexity, low memory overhead and low energy consumption per nano-node is highly required. In this paper, firstly we propose a virtual routing function for nano-network by externalizing the routing decisions and computations to be computed externally on SDN/NFV programmable computational architecture, which makes the intelligence of the system is located on the external NFV controller, since the nano-network function will be seen as a component of the network that can be managed and provided through service delivery frameworks. Also, the management of data routing will be completely centralized and externalized from nano-routers up to the NFV layer. Secondly, we propose a path discovery protocol for nano-network that uses a routing metric suitable for nano-nodes' constraints. This protocol will be complied and implemented on the external SDN/NFV architecture. The proposed routing scheme depends on the density of nano-routers, i.e., the probability of having nano-routers in a specific cell inside the area of interest taking into consideration that nano-routers have no fixed positions, while they are moving, so there is a probability of nano-routers' existence in a specific cell. The analytical evaluation of the proposed protocol shows that the higher the probability of having nano-routers

Table 2: Comparison between PBPD protocol and other routing protocols proposed in the literature.

Routing Protocol	Position Awareness	Node Deployment	Energy Consumption	Computational Complexity	Scalability	Network Structure	Node Mobility	Routing Path
CORONA	Yes (Hop counts to the anchor)	Deterministic	High	Low	Limited	Flat	Static	Multi-path
SLR	Yes (Hop counts to the anchor)	Deterministic	High	Medium	Limited	Flat	Static	Multi-path
AODV	No	Random	High	High	Good	Flat	Mobile	Multi-path
DEROUS	Yes (Hop counts along the radius of the beacon)	Deterministic	High	Low	Good	Flat	Static	Multi-path
MHTD	Yes (Distance to the nano-controller)	Random	Low	High	Good	Hierarchical	Mobile	Single-path
ECR	Yes (Based on layers)	Random	Low	Medium	Good	Hierarchical	Mobile	Single-path
PBPD	No (Based on density)	Random	Low	Low	Good	Hierarchical	Mobile	Single-path

across the path, the higher the probability of successful end-to-end transmission. Also, the lowest delay (weight) path to the destination may not be the best path, as it may provide a low probability of successful end-to-end transmission. Moreover, it is recommended to use three up to five nano-routers inside the cell during the routing process, because this range will satisfy high probability of successful end-to-end transmission, while maintaining lower cost and energy consumption of nano-routers. The qualitative analysis with other routing protocols showed that our proposed PBPD protocol is:

- Single-path protocol follows a hierarchical nano-network structure, so it leads to significant energy saving inside nano-nodes.
- PBPD protocol follows a random node deployment method, so it supports nano-nodes mobility. Hence, it will be more applicable to dynamic nano-network applications, because it considers a continuous sequence of snapshots or frames for the nano-network topology. Each snapshot represents the distribution of nano-nodes at a certain time. This snapshot has a lifetime called topology lifetime, which has to be greater than or equal the processing time to guarantee that the required actions and computations have been achieved on a specific topology, before it changes to a new one.
- Due to the externalize of computations and calculations to an external SDN/NFV system, PBPD protocol has low computational complexity with good scalability thanks to the rule of NFV. Moreover, it provides more flexibility due to the decoupling between the control plane and data plane because of SDN, which gives PBPD protocol a prominence over other routing protocols that use the local computations on the nano-router for data routing.

Our future work will simulate the performance of the PBPD protocol using one of the nano-network simulators such as NanoSim, BitSimulator and TeraSim [41] trying to provide a quantitative comparison with other routing protocols discussed in the literature. Moreover, we will study the possibility of proposing different Virtual Network Functions (VNFs) for nano-network and figure out how these VNFs can be composed together to create a nano-network service. Path discovery function and clustering formation function can be examples for this work, trying to implement a practical network service chaining for nano-network. Also, we will study how to create SDN/NFV test-bed for this implementation by orchestrating one of the nano-network simulators with different types of most popular SDN controllers integrated with different types of VIMs, VNFMs and NFVOs. In addition, we will study an appropriate clustering scheme for the nano-network taking into consideration the corresponding limitations in processing and energy consumption.

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Author Statement

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The authors whose names are listed below certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patentlicensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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