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## Towards nanoscale interconnect for system-on-chip

Olimjon Yalgashev

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# SPIM

## Thèse de Doctorat



école doctorale sciences pour l'ingénieur et microtechniques  
UNIVERSITÉ DE TECHNOLOGIE BELFORT-MONTBÉLIARD

Thèse présentée par

Olimjon YALGASHEV

pour obtenir le

Grade de Docteur de

l'Université de Technologie de Belfort-Montbéliard

Spécialité : **Informatique**

### **TOWARDS NANOSCALE INTERCONNECT FOR SYSTEM- ON-CHIP AND WIRELESS NANOSENSOR NETWORKS**

Soutenu le 29 octobre 2015 devant le Jury :

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## Chapter 1: General Introduction

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## 1.1 The research domain

General context: Nanocommunication, wireless nanosensor networks

Specific context: Interconnections and communication protocols in the terahertz band, applications to wireless on-chip networks and wireless nanosensor networks.

## 1.2 Background

Due to excessive use of information in today's society, data traffic increased in networks. Consequently, requirements to high-speed wireless communication emerges. As a solution of the issue, alternative communication approaches like optical interconnections, Radio Frequency Interconnect (RF-I) transmission lines and metal-oxide-semiconductor (CMOS) Ultra-Wideband (UWB) wireless interconnect technology have been proposed. The usage of the nanoscale communication might be one more solution of the issue that is rapidly gaining the attention of researchers, thanks to the nanotechnology.

Recently, designing electromagnetic-based (EM-based) communication approach is proposed in the terahertz band [1] [2] [3] [4]. The terahertz band falls between microwave and infrared bands in the electromagnetic spectrum. Microwave and infrared bands are well investigated and there are a list of applications in the vital activity. The band could present ultra-high-speed, efficient and scalable methods of inter-core communication in wireless on-chip networks. This novel approach will expectedly fulfill the stringent requirements of communication-intensive on-chip applications due to its high bandwidth. This makes terahertz band communication a promising technology to enable next-generation massive multicore architectures.

### 1.3 Problem statement

The main components of Wireless Nanosensor Network (WNSN) are nanodevices with some features such as saving small information, performing simple calculations, and sensing the surrounding environment [5]. Nanodevices could be connected with each other to perform common tasks in a distributed manner and the obtained network is envisaged to expand the capabilities and applications of single nanodevices. Nanodevices such as chemical sensors, nano-valves, nano-switches, or molecular elevators, cannot execute complex tasks by themselves [6]. Data exchange and commands among nanodevices enable them to work together and synchronously to execute difficult tasks such as drug delivery or indicate analysis of blood in human organism. Thus, using nanocommunication enables number of application scenarios, such as monitoring and controlling of chemical agents in ambient air. In designing nanocommunication, some applications might use nanodevices that are located over a large area (from meter to kilometer). In such cases, controlling a special nanodevice is very difficult issue, since the size of nanodevices is measured in nanometer. Therefore, WNSNs should be implemented to interact with remote nanodevice through a certain nanocommunication mechanism.

Communication at the nanoscale paradigm is rapidly gaining the attention of researchers, thanks to the nanotechnology. Taking into account that small-sized nanodevices with limited sensing, computation, storage and power capabilities form WNSNs, existing networking architectures and communication protocols should be re-designed considering nanoscale communication mechanisms. In other words, to design new nanoscale applications, existing communication technologies should be reviewed, taking into account communication and power consumption requirements. Existing



networking architectures and communication protocols should be rethought considering nanoscale communication methods [7]. Thus, following main issues should be tackled:

- Existing communication technologies should be re-designed (viewed) for developing new nanoscale applications;
- Nanodevices and its components together with methods for controlling and monitoring these devices should be developed;
- New architectures, topologies and protocols for nanocommunication should be developed.

In this thesis, we are tackling the first issue by exploring this new communication paradigm in the context of information dissemination in WNSNs. Primarily, alike any wireless networks that use broadcasting mechanism for information dissemination, redundant broadcasts and packet collisions will be observed in WNSNs. We have adapted the existing mechanism that resolves broadcast storm problem for WNSN.

Secondly, we have tackled transmission range issue. Due to high transmission range in dense network redundant transmissions, and consequently requirement to energy (consumption) will be high. Contrariwise, low transmission range is a cause of disconnected nodes and low packet delivery ratio (PDR). Therefore, transmission range should be adapted according to network density. We have proposed a mechanism for adapting transmission range considering aforementioned issue.

Thirdly, we deal with the third issue by investigating this new communication paradigm in the context of Nano-NoC design. We first studied existing nanonetworking architectures and communication protocols and then implemented these nanonetworking

mechanisms to develop new techniques for modeling, designing, and simulating network on a chip (NoC) at nanoscale.

### **1.4 The contribution**

The main objective of this thesis is to implement the electromagnetic-based communication mechanism for WNSN and Nano-NoC design. As part of the thesis, we first investigated the performance of the EM-based broadcasting mechanism for nanocommunication. Obtained simulation results showed that the transmission range and network density depends on to each other. For example, in high dense network, increasing the transmission range allows quickly the network to sustain higher throughput while maintaining low latency. In low dense network, even with high transmission range, the network could sustain lower throughput. These results confirm the research hypothesis stating that different transmission range values need to be assigned based on network density. Therefore, adaptive approaches are required to allow tuning the transmission range of nanonodes based on network density. According to these results, we proposed an adaptive transmission range approach that allows nodes to select the best suitable transmission range in order to increase network connectivity. Results showed that this approach provides a good throughput while minimizing latency.

Flooding mechanism, which is one of the simplest routing protocol, causes to redundant transmissions and receptions. Moreover, many message collisions will be observed. Especially, incorrect tuning of transmission range might be catastrophic regarding with excessive transmissions and message collisions. Since we investigate EM-based WNSNs, requirements to energy consumption should be low. Redundant transmissions and receptions are the causes of high energy consumption. Therefore,

protocols that reduce redundant retransmissions are required. Accordingly, several modified flooding schemes have been suggested in literatures for MANETs. We have adapted counter-based scheme in context of WNSN and called the algorithm efficient flooding algorithm. Simulation results show that the algorithm is much effective than simple flooding algorithm. We have minimized message collisions and number of transmissions (TX) and receptions (RX), at the same time we achieved acceptable results for average latency and packet delivery ratio.

In parallel to this study, we have also investigated EM-based broadcasting mechanism as a new communication medium for Nano-NoC design. We also implemented a XY-routing algorithm into Nano-NoC and evaluated its performance to compare with the basic broadcasting algorithm. Several traffic patterns have been used for performance evaluation of Nano-NoC, mainly Uniform, Bit-Reversal, Shuffle and Transpose. Performance metrics such as latency, throughput and energy consumption, are evaluated and reported in order to show the behavior of Nano-NoC when varying the number of nanonodes and transmission ranges. In summary, within the scope of the thesis, the main contributions are as follows:

- Performance evaluation of WNSNs is conducted;
- An efficient flooding algorithm is developed for WNSNs;
- Adaptive transmission range algorithm is developed for WNSNs;
- XY routing algorithm is introduced for Nano-NoC and investigated considering different types of nodes and traffic patterns.

## **1.5 Organization of the dissertation**

### ***1.5.1 General presentation***

The thesis is structured in six chapters, including a general introduction, conclusions and perspectives. The first chapter provides the general context of our study including the problem statement, the objectives and the contributions. The second chapter overviews the main concepts of wireless sensor networks, including basics and design methods of WSNs, and presents existing work from literature. The third chapter introduces efficient flooding algorithm that reduces redundant broadcasts in WSNs. The fourth chapter presents the performance of the proposed adaptive transmission range approach together with obtained simulation results. The fifth chapter presents Nano-NoC as a new communication medium for SoC design. Finally, we present conclusions and perspectives in the sixth chapter.

### ***1.5.2 Global view***

- Chapter 1: General introduction
- Chapter 2: State of the art
- Chapter 3: Efficient flooding algorithm
- Chapter 4: Adaptive transmission range approach
- Chapter 5: Nano-NoC for SoC design
- Chapter 6: Conclusions & Perspectives

### ***1.5.3 Chapter contents***

#### ***Chapter 1: General Introduction***

The General Introduction chapter provides the background information about the wireless networks and possible communication methods in the nanoscale. The terahertz band communication method is presented as one of the solution designing nanoscale NoC (Nano-NoC). The current trends and problems of the area are presented. Finally, the contribution and the organization of the dissertation are presented.

### ***Chapter 2: State of the art***

This chapter describes the main concepts of wireless based networks, nanocommunication mechanisms and classifications. Architecture, base components, interconnection model, information dissemination mechanisms and simulation tools of electromagnetic based WSNs are highlighted. Moreover, advantages and disadvantages of electromagnetic based communication mechanism are presented and compared with other communication methods.

### ***Chapter 3: Efficient flooding algorithm***

In this chapter, the usage of efficient flooding algorithm for WSNs is highlighted. First, we described existing issues of flooding mechanism. Secondly, we highlighted the importance of reducing redundant transmissions and receptions. Then we propose efficient flooding algorithm for WSNs. Simulations are presented to show the effectiveness of the proposed algorithm.

### ***Chapter 4: Adaptive transmission range approach***

In this chapter, an adaptive transmission range of electromagnetic-based communication mechanism is introduced. Simulations are conducted with fixed and adaptive transmission ranges to show the efficiency of the proposed approach in terms of throughput and latency according to the network density.

***Chapter 5: Nano-NoC for SoC Design***

In this chapter, the performances of EM-based nanocommunication mechanism as an on-chip interconnect for SoCs are evaluated. The aim of the study is to analyze the behavior of communication in Nano-NoC. Several performance metrics, such as the average latency, the throughput and the energy consumption are analyzed by varying the number of nanonodes and the transmission range. Two routing techniques, flooding and XY routing, are evaluated using four traffic patterns, such as Bit-Reversal, Shuffle, Transpose and Uniform. A 2D Mesh-like nano-OCI architecture is considered.

***Chapter 6: Conclusions & Perspectives***

In this part of the dissertation, we present the summary of the work and future work, i.e., perspectives will be listed in the end of the chapter.

## Chapter 2: State of the art review

This chapter is dedicated for describing the main concepts of wireless networks, mechanisms and classifications of nanocommunication. Consequently, architecture, base components, interconnection model, information dissemination mechanisms and simulation tools of electromagnetic based WSNs are highlighted. Moreover, advantages and disadvantages of electromagnetic based communication mechanism are presented and compared with other communication methods.

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## 2.1 Introduction

Ad hoc networks are self-organizing networks that are created from equivalent stations without wired infrastructure, i.e. these networks have no stations with higher privileges or access points. Ad hoc communications are present in Wireless Sensor Networks (WSNs), Mobile Ad hoc Networks (MANETs), Vehicular Ad hoc Networks (VANETs), Personal Area Networks (PANs), Body Area Networks (BANs) and Wireless Nanosensor Networks (WNSNs). The emergence and development of wireless communications, microelectromechanical systems technology, and digital electronics has allowed these networks to be widely deployed and explored. The evolution of these systems includes the development and improvement of wireless communication systems, data processing, etc. Furthermore, wireless ad hoc applications play an important role in various fields such as healthcare system, security, business, environment, etc. For example, sensors could be used in many environments with different conditions including vehicular movements, detection of certain obstacles on the road, vehicular speed, temperature, humidity, pressure, etc.

Recently, Wireless Nanosensor Networks have been emerged as a typical subclass of WSNs, but at nanoscale (1-100 nanometers). Nanometer (nm) is equal to one-billion of a meter ( $1 \text{ nm} = 10^{-9} \text{ m}$ ). The objects on nanoscale include virus, carbon nanotubes, DNA, etc. The vision of WNSN could achieve the functionality and performance of today's WSN with the exception that the dimension of devices is measured in nanometer and they perform very simple sensing and computation tasks. In addition, nodes of WNSNs are assumed to be mobile and rapidly deployable. However, in order to develop WNSN applications and services, still many research issues have to be investigated. In this



chapter, firstly, we present existing wireless ad hoc network types together with their basics and fundamentals.

## **2.2 Wireless Ad hoc Networks**

As mentioned before, wireless ad hoc networks are self-organizing and infrastructure-less networks that include equivalent stations. Every station participates in routing process by forwarding data to other stations according to network connectivity [8]. Wireless ad hoc networks could be categorized as follows: Wireless Sensor Networks (WSN), Mobile Ad Hoc Networks (MANETs), Vehicular Ad hoc Networks (VANETs), Personal Area Networks (PANs) and Body Area networks (BANs). Table 2.1 illustrates the difference and common characteristics of WSN, MANET, and VANETs, in terms of nodes storage, communication carrier, energy consumption, etc. that are described in the rest of this section.

### ***2.2.1 Wireless Sensor Networks***

A wireless sensor network is a particular type of ad hoc networks mainly dedicated for environment monitoring. WSN devices have a small processor, a short-range wireless transceiver, and advanced sensing abilities for measuring and monitoring thermal, pressure, acoustic changes of an environment. WSN sensors exchange information with each other to give a user a global view of the monitored environment. User can access the gathered information from one or more gateway node(s). Sensor networks are expected to bring a breakthrough in the way natural phenomena are observed: the accuracy of the observation will be considerably improved, leading to a better understanding and forecasting of such phenomena. The expected benefits to the community will be considerable [10].

WSNs efficiently affect many areas of life, including civilian and military applications. WSN could be applied for monitoring different events of huge areas, for example sensing seismic effects or forest fires. WSN sensors that equipped with a battery, processing and wireless communication abilities, should be placed in important parts of an environment such as on the top of a hill or in locations with wide view. Sensors cover a few hectares area and have capabilities to connect with neighboring sensors. The sensor node gathers water data (e.g. temperature, flow velocity and direction) and analyzes water makeup to detect particular particles. Each sensor have an infrared camera that able to detect thermal variations. WSN sensors know its geographic position via localization algorithms [11], expressed in terms of degree of latitude and longitude. This can be accomplished either by equipping every node with a GPS receiver, or, since in this scenario sensor position is fixed, by setting the position in a sensor register at the time of deployment. Sensors exchange information with neighbor sensors for detecting unusual events that might be the reason for catastrophic situations. The external device collects data coming from sensors. If catastrophic situation is detected, an emergency procedure will be started. A sensor that detects the unusual event connects with its neighbors to verify if other sensors have detected the same event; then, it tries to accurately determine the geographic position of the hazard. If other sensors have detected the same unusual situation, this can be accomplished using triangulation techniques. Finally, the external device alerts (location, severity rating, etc.) about the unusual event [10].

In addition, WSNs are deployed widely in other and various applications such as structural health monitoring [12], and monitoring of agricultural environment [13]. For example, in [13], WSN-based environmental and soil sensors are used to collect environmental and soil information on the outdoors and collect location information using

GPS modules for producers. WSN technology was also used for habitat monitoring [14]. In fact, habitat and environmental monitoring represent an important class of sensor network applications. Furthermore, WSNs offer great promise for information capture and processing for military and defense applications. Military is using this concept rigorously for their advancement in warfare and field [15]. A WSN is typically composed of nodes with the same features. The number of nodes of a WSN could range from few tens to thousands and typical WSN covers quite large geographical region, which means single hop communication between nodes is not possible in many scenarios.

### ***2.2.2 Mobile Ad hoc Networks***

A mobile ad hoc network is a special form of ad hoc networks, it differs from WSN with its node mobility features. It is a self-configuring network of autonomous and mobile nodes (devices) that not rely on a predefined architecture. Nodes move independently of other members of MANET without any condition and in any direction and at any time. Communication among MANET nodes occurs via wireless links while maintaining their connectivity in a decentralized way. A node changes frequently its links with other nodes without notice, thus routing in such networks is a challenging issue. The main role of each node in a MANET is to continuously maintain the information required to its own usage as a host and be a router for neighbor nodes enabling the information transmission.

Combining WSN and MANETs technologies provide powerful, mobile and highlight applications in various domains. It has been shown in literature that most of the cooperative networks developed are based on the coordination of different spatially distributed nodes within a wireless network, such as MANET and WSN. In [16], a conceptual framework of cooperative network was proposed for coordination among different wireless networks to achieve perfect overall network performance with anytime

and anywhere connectivity. Several network designs and technologies are available in the wireless domain. Each one of these technologies and designs came up to fulfill specific technological needs and requirements.

Much research works have been conducted and targeted the development of applications and prototypes. Among these applications, MANET principle is applied for military communication and operations; emergency services (disaster recovery, policing and firefighting, rescue operations, etc.); commercial and civilian environments (e-commerce, vehicular services, sports stadiums, etc.); home and enterprise networking (home/office wireless networking, personal area networks, etc.); education and learning (virtual classrooms, ad hoc communication during meeting, etc.); context aware services (information services, follow-on service, etc.); sensor networks (data tracking, movement detection, smart sensors, etc.) [17].

In designing successful communication among mobile nodes, MANET resources play an important role. In cases when receiver node located inside transmission range of sender node, data transmission is performed with a single hop. In all other cases, data transmission is possible through multi-hop path, if the path is available between them. MANETs have unique characteristics and they have many common attributes and operations with other traditional networks [18].

### ***2.2.3 Vehicular Ad hoc Networks***

Vehicular ad hoc networks are special subclass of MANETs. The nodes of the VANETs are vehicles and roadside units, communication occurs among these nodes. VANETs are more dynamic than MANETs due to the rapid network topology changes. VANET nodes are equipped with embedded calculators, sensors and wireless

communication technologies. Unlike MANETs where nodes can freely move in a certain area, the movements of vehicles in VANETs is always at high speed and could be predicted, because it is dependent on streets, traffic and specific rules. Communication between nodes in VANETs is less reliable due to the high mobility, dynamic topology and different traffic patterns compared to MANETs [19].

Due to the large requirement of intelligent transportations systems (ITS), VANET constitutes an emerging branch of wireless ad hoc network where communication can be conducted between vehicles, vehicle to vehicle (V2V), and/or between vehicle and infrastructure (V2I) [20], [21], [22]. It is seen as hopeful technology for efficiency, safety, comfort and assistance of users in ITS [9]. In a VANET, routing issue and maintaining the communication between vehicles considering the highly dynamic topology of the network, which is frequently disconnected, and mobility constraints are important challenges. In last decades and with the aim to increase the intelligent and safety degrees in transportation systems, VANET technology has been an attractive research area of many research communities [23] [24].

As proved in many research works as well as in driving real conditions, VANET technology may not maintain communication connectivity and does not guarantee timely detection of dangerous road conditions when the network density is low. Since VANET nodes have high velocity, they could be rapidly disconnected from each other, consequently, in some cases, density of VANET might be low and not all nodes in VANET might receive messages. Combining the VANET technology with other technologies is one of the alternatives in order to address this problem. The integration of WSN and VANET overcomes the inherent limitations of alone usage of VANET [21]. In this research work, the authors have proposed a VANET-WSN system for timely

detecting road conditions and helps to connect partitioned segments of the VANET. This system has been developed to collect, process, share, and deliver real-time information about road conditions in order to make roads safer, cleaner and smarter. As detailed in [22], [25], [26], and [27] sensor nodes can be deployed along the infrastructure with higher density than current roadside stations enabling a strong connectivity with the VANET. The sensor nodes can sense the road conditions, collect and process the sensing data to find out useful information for safe driving, and deliver the information to vehicles. Some examples showing the powerful of the integration of WSNs with VANETs in preventing road accidents are given in [21]. Among these examples, deploying WSN along rural roads in order to prevent vehicle-animal collision; detecting, relaying and propagating the information about bad infrastructures and roads by connected sensors to any vehicle approaching the dangerous area. Furthermore, VANET-WSN concept was used for collecting state message from roadside sensors for the routing protocol with the aim to assist drivers and for driving safety. WSN was used also as a solution for smart transportation [28]. In fact, low power consumption of node sensors, their wireless distribution and their flexibility without cable restrictions, WSN have been used for transportation information collection and communication. These wireless networks have proved their effectiveness in the field of ITS.

#### ***2.2.4 Wireless Personal Area Networks***

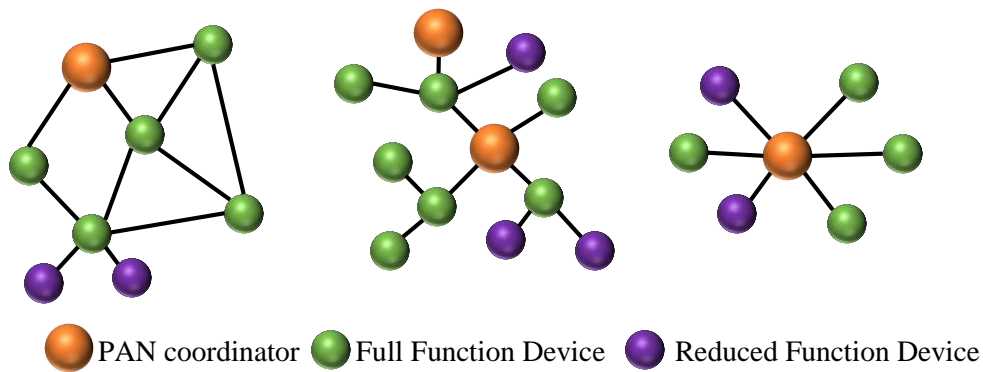
A wireless personal area network is a wireless ad hoc data communications system. It is designated based on the standard IEEE 802.15. WPAN could be used to connect different independent devices, such as computer hardware and home appliances, communication devices, etc. The physical and link layers are regulated by the standard IEEE 802.15.4. WPANs differ from other types of ad hoc networks in both size and scope.

Operating range WPAN ranges from several meters to several tens of centimeters. WPAN may be deployed using different network technologies, such as IrDA (Infrared Data Association), Wireless USB, and Bluetooth. The main objective of implementing WPAN is removing any cables from the phone, and if possible, and from local networks. It is obvious that currently Bluetooth cannot supplant 802.11 least because of the restrictions on the maximum size of the network. The frequency of WPAN is 2.4 GHz, therefore it is one of the low cost networks that mentioned other sections of the chapter [29].

Unobtrusive devices, such as personal computers, smartphones, cell phones, and peripherals are mostly used in designing WPAN for communication and interoperate with each other. These devices can be used in order to improve the ability to perform productive individuals.

It is established close working relationships with Special Interest Groups such as Bluetooth and Industry Consortia namely HomeRF. Depending on market requirements and technical solutions, coverage area of WPANs is from 0 to 10 meter range. In its early stage, the data rates was less than 1 Mbit/s. Generally, devices of WPAN maintain low power consumption, small size and low cost.

A key concept in WPAN technology is known as plugging in. According to the rules of WPAN, if WPAN devices are close or comes close each other, they should be able to communicate. Other features of WPAN could be highlighted as following: each device of WPAN have ability to lock other devices and unauthorized access to information, and preventing needless interference.



**Figure 2. 1 WPAN topologies**

Depending on application requirements, WPAN can be designed in one of two topologies: star or peer-to-peer (P2P). There are three different types of devices in the WPAN: PAN coordinator, Full Function Device (router) and Reduced Function Device (end device) shown in the figure 2.1 [30].

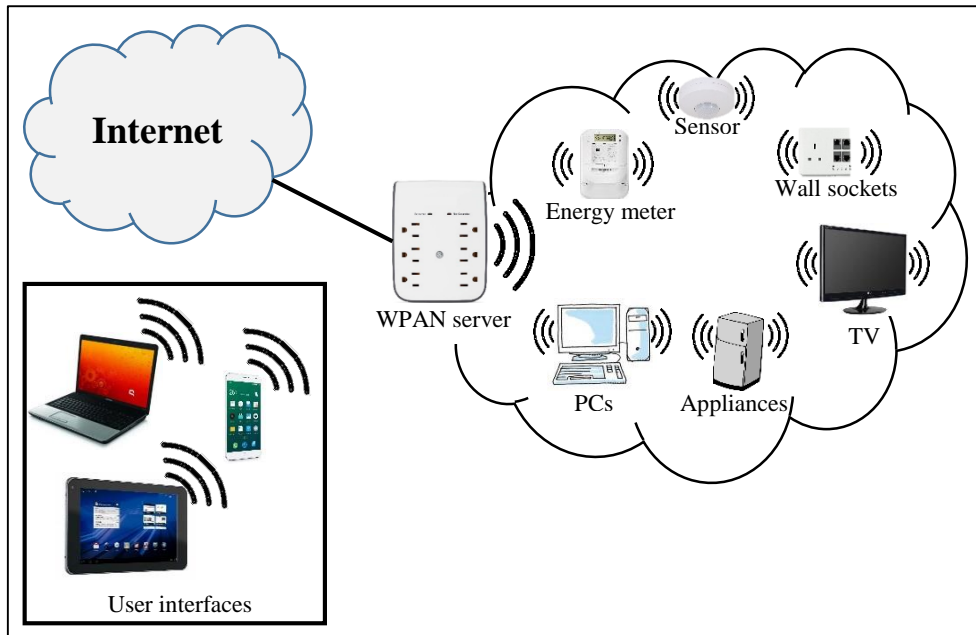
Coordinator forms paths of network tree and can communicate with other networks. Each network has a coordinator and it can store information about the network. Router (Full Function Device) can act as an intermediate node, it transfers data coming from other devices. The function of end device allows it to communicate with the parent nodes, such as coordinator or router. End device (Reduced Function Device) cannot transfer data to other type of devices. This attitude allows end devices to be in IDLE mode and save energy.

In case of a star topology, communications will be established between individual devices and a central controller that called the PAN coordinator. The P2P topology is also works with the PAN coordinator. In this topology, any network devices can communicate with each other, if only there are appropriate channels [30].

PAN coordinator can be powered by AC power and other devices are often powered by batteries. Applications that prefer star topology include home automation system,



peripherals, toys, and various devices associated with health care. WPAN could be used in the field of home entertainment and control as depicted in figure 2.2.



**Figure 2. 2 Home control using WPAN**

Wireless personal area networks (WPANs) are unsuitable in medicine and some application environments. They also do not support several important requirements in health care system, such as reliability, QoS, higher energy consumption, low data rate. Most of these issues are solved by using Body Area Networks in health care system.

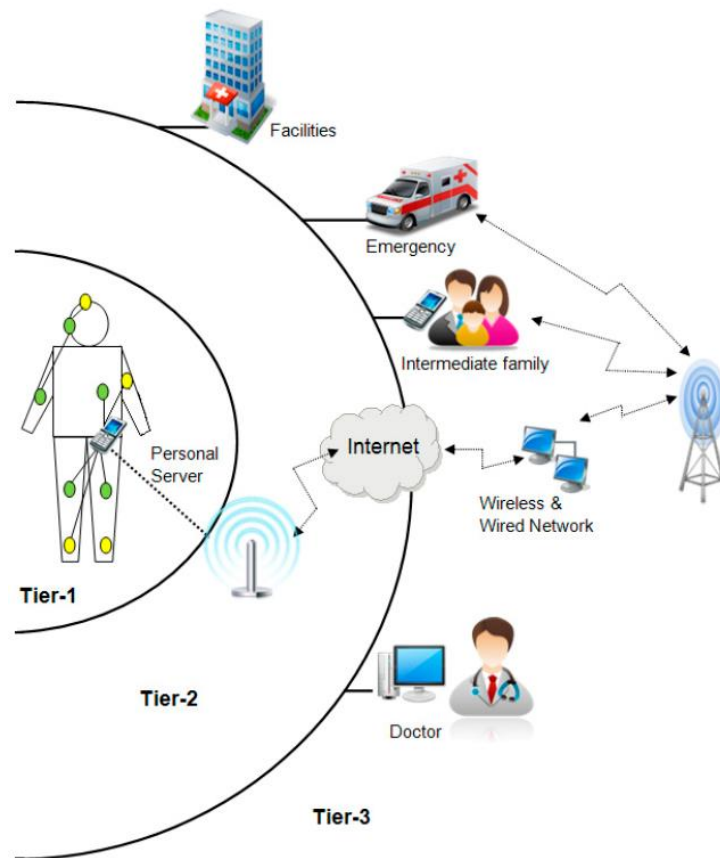
### **2.2.5 Wireless Body Area Networks**

Current achievements of information technologies allows decreasing size of electronic devices and increase their capacities. These small-sized devices (or sensors) can be used in medicine to monitor human, for example, analysis of blood composition. Several materials are suitable with human body; these materials can be used in the implementation of sensors. Wireless Body Area Networks (WBANs) are communication networks of sensors placed on inside or around the human or any organic body with the intent to

monitor. IEEE 802.15.6-2012 is a standard for short-range, wireless communications in the vicinity of, or inside, a human body (but not limited to humans) [31].

IEEE 802.15.6 standard classified WBAN nodes as following: Implant Node, Body Surface Node, External Node, Coordinator, End Node and Relay [31]. Authors of [32] suggested node classification by functionality: Personal Device, Sensor and Actuator.

Personal Device is responsible to collect information that coming from sensors or actuators and transfer collected information to another network. Sensors might be placed inside or outside of body, they sense events or physical status of a body and send them to Personal Devices. Sensors can be of different types depending on their usage area. They can sense temperature, humidity, blood glucose, etc. Actuators interact with the user upon receiving data from the sensors [32]. WBAN could constitute ranging from 6 to 256 nodes [33] with scalable configuration. The ring topology is proposed for WPANs in The IEEE 802.15.6. In this case, personal device could be placed in the center of body, for example in waist. The Communication Architecture of WBANs is well presented in [32] as depicted in the figure 2.3.



**Figure 2. 3 Communication Tiers in a WPAN [32]**

Authors separated WBAN communication architecture into three tiers: (i) Tier-1: Intra-WBAN communication; (ii) Tier-1: Intra-WBAN communication; (iii) Tier-3: Beyond-WBAN communication. Transmission range of Tier-1 covers around 2 meters inside (around) human body. In the Tier-2 WBANs can communicate with daily networks, such as internet or cellular network. In Tier-3, doctors or family members (i.e., family) that have access to the information can observe the changes of patient body.

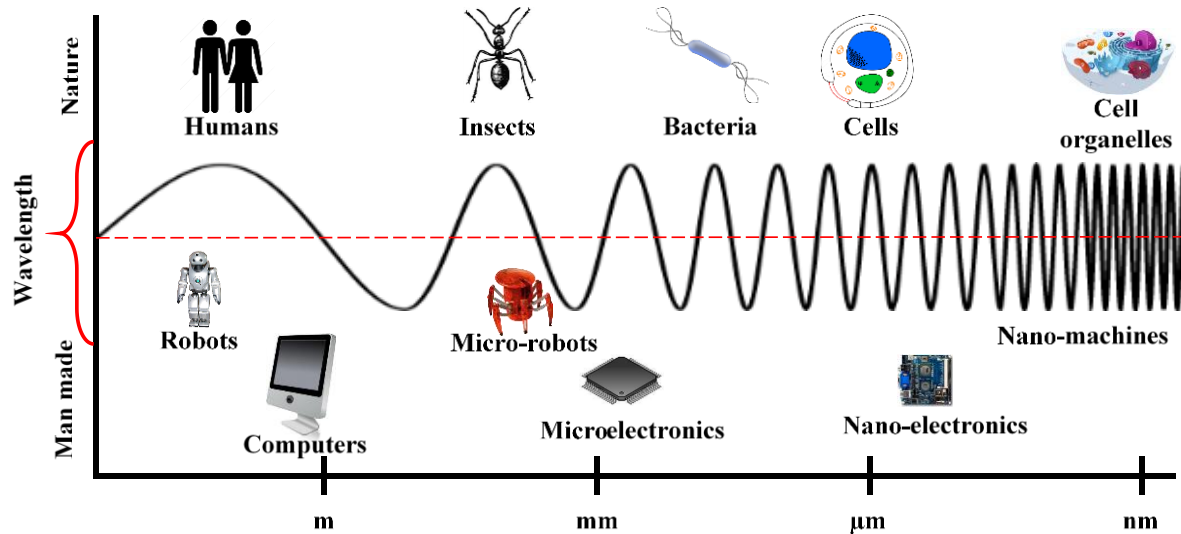
WPAN could be used different directions of life, such as healthcare, sport, military, entertainment, etc. WPAN applications could be separated into two directions: medical and non-medical applications.

Medical applications that use WBAN helps continuous monitoring changes in body patient, for example sensors can detect easily blood pressure, heartbeat and temperature. When abnormal events are detected, gateway sends the information via a cellular network or the Internet [34].

Non-medical WBAN applications could be useful in emergency, secure authentication, entertainment, etc. WBAN sensors can easily detect content of the air. If an alarm condition occurs, like medical applications, gateway can deliver the information to homeowner or corresponding organizations. WBANs could be used to recognize and store biometric data, such as fingerprint, facial patterns in the security field.

#### ***2.2.6 Wireless Nanosensor Networks***

Richard Feynman, the Nobel laureate physicist in 1959, in his famous speech entitled “There is Plenty of Room at the Bottom”, described for the first time how the manipulation of individual atoms and molecules would give rise to more functional and powerful devices [5]. This was the vision of many researchers that are willing to explore thing but at nanoscale. For example, authors in [5] have stated that nanodevices could be classified following categories: man-made (e.g., electromechanical) and nature-made nanodevices (e.g., molecular motors) as illustrated in Figure 2.4.



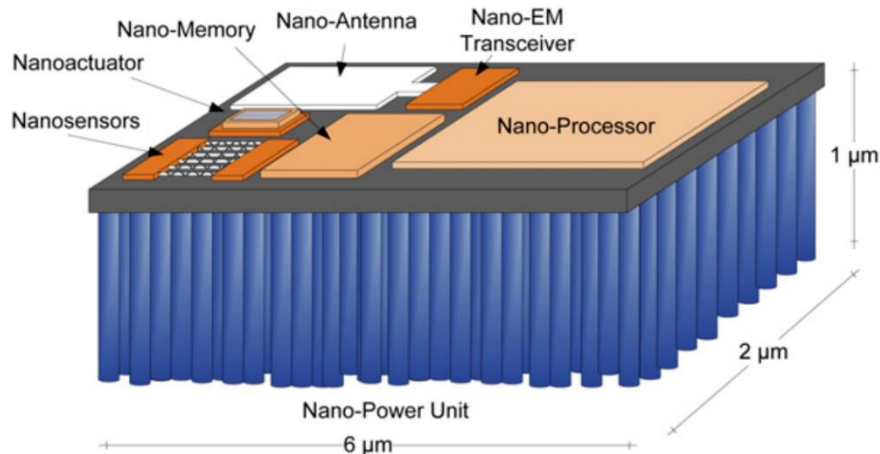
**Figure 2. 4 The vision of shifting from top-down to bottom-up machine design**

The aim of nanotechnology is designing nanodevices with new abilities starting from unique characteristics of nanomaterials or nanoscale objects [35]. The vision of electromagnetic (EM) based WNSN could achieve the functionality and performance of today's WSN with the exception that devices size is measured in nanometers and up to hundreds or thousands of nanometers physically separate channels. In addition, nanodevices are assumed to be mobile and rapidly deployable. Therefore, ad hoc communication mechanisms are required to allow these entities to exchange sensed information between each other and with external units.

In this research direction, nanotechnology has emerged as a field of manipulating individual at atoms or molecules levels. According to the national nanotechnology initiative, nanotechnology is a research field for manipulating objects with dimensions from 1 to 100 nanometers. At this scale, a nanodevice can be considered as the most basic functional unit. Nanodevices are nanoscale devices that might perform sensing and simple computation tasks [36]. Nanodevices can be used as base blocks for designing complex systems such as nanorobots, nanomemory or nanoclocks [5]. Full-featured WNSN

nanodevices should have sensing, actuation, power, processing, storage and communication abilities for sensing events of surrounding environment and propagate it to other members of WNSN [35]. Presently, applications that applied nanodevices work independently and perform tasks, such as sensing and actuation [7]. In the future, nanotechnology could provide a novel tools for monitoring and controlling nanoscale objects.

There are different types of nanodevices, such as nanosensor, nanorouter and nanogateway (interface). Functionality of nanosensors is to sense events around and broadcast the event to neighbors by using mechanical, acoustic, chemical or electromagnetic communication methods. Authors in [1] have proposed a nanosensor architecture as illustrated in Figure 2.5. Other type of nanosensors could absent nanosensor since they just forward information.



**Figure 2. 5 Nanosensor device [1]**

The WNSN applications are unlimited and they can be applied to any field of life. WNSN applications could be classified as following: biomedical, environmental, industrial and military applications. Moreover, considering of using nanotechnologies in

manufacturing of different nanodevices, WNSN could be used also in another life activities such as consumer electronics, lifestyle, home appliances, etc. Modern biomedicine needs the use of nanodevices and WNSN, since biological nanodevices will be developed using nanotechnology inspiring of nanoscale objects to interact with organs and tissues. There is a list of advantages of using such networks in the field of nanomedicine, such as size, biocompatibility, biostability, etc. Since WNSN applications play an important role in healthcare domain, compatibility of these nanodevices with biological environment is very important issue, and it is called the biocompatibility issue. The main reason is related to rejecting implants and drugs by organisms. The solution of biocompatibility problem, nanotechnology is used to designing nanodevices that are more suitable with biological organisms. When it comes to the use of WNSN in biological environment, biostability is critical issue in this area. Biostability is the ability of nanodevices to maintain its integrity after implantation in biologic environment. Immune system support, bio-hybrid implants, drug delivery systems, health monitoring, and genetic engineering are good examples for applying WNSN.

Furthermore, WNSN is suitable for developing novel nanomaterials, manufacturing processes and quality control procedures, mainly in the field of water quality control and functionalized materials. It can be also used in several applications of the military field. As pointed before, the range covered by WNSN is short. The deployment range of WNSN can be changed depending on the application. Battlefield monitoring require a dense deployment of WNSN over large areas, it could be solved by placing soldiers performance monitoring systems in their body. Military applications that could use WNSN are nuclear, biological and chemical defenses, nano-functionalized equipment. Due to the fact that nanodevices are developed by inspiring biological objects found in

nature, they can also be applied in environmental fields, for example biodegradation, animals and biodiversity control, air pollution control [35].

### ***2.2.7 Comparison of Ad hoc Wireless categories***

Table 2.1 illustrates the difference and common characteristics of WSN, MANET, and VANETs, in terms of nodes storage, communication carrier, energy consumption, etc. that are described in the rest of this section.

Sensors are network devices that monitor and measure changes of different type of physical condition like temperature or pressure and send them to other members of a network. The components of MANET are PDAs, mobile phones, smart phones that move slowly and randomly. Vehicles and roadside units are nodes of vehicular communication system that provides different warnings and road information [9]. Molecules or hand-made tiny devices so-called nanodevices (nanodevices and nanosensors) are components of a WNSN.

WSNs/WNSNs are based on broadcast communication, and wireless ad hoc networks mostly use point-to-point communication. Nodes of WNSNs are tiny size of nanodevices that equipped with nanobatteries accordingly to their size. Therefore, devices of WSNs/WNSNs are limited in power. These networks use also broadcasting protocols, and consequently, power consumption of WSN/WNSN is a major concern.

| <b>Requirements/<br/>Characteristics</b> | <b>WSNs<br/>WNSNs</b>                      | <b>MANETs</b>            | <b>VANETs</b>                  | <b>WPANs</b>                               | <b>WBANs</b>                               |
|--|--|--------------------------|--------------------------------|--|--|
| <b>Nodes</b>                             | Sensors,<br>nanosensors                    | Devices<br>(smartphones) | Vehicles,<br>Roadside<br>units | Home<br>appliances                         | Body sensors                               |
| <b>Communication<br/>infrastructure</b>  | Infrastructure-<br>less and<br>centralized | Infrastructure-<br>less  | Infrastructure-<br>less        | Infrastructure-<br>less and<br>centralized | Infrastructure-<br>less and<br>centralized |



|                                |                      |          |          |                            |                            |
|--------------------------------|----------------------|----------|----------|----------------------------|----------------------------|
| <b>Power consumption</b>       | High                 | Medium   | Low      | High                       | High                       |
| <b>Mobility</b>                | Limited *            | Low      | High     | Low                        | Low                        |
| <b>Communication mechanism</b> | Wireless, molecular* | Wireless | Wireless | Wireless (IrDA, Bluetooth) | Wireless (IrDA, Bluetooth) |
| <b>Data storage</b>            | Low                  | Medium   | High     | Low                        | Low                        |
| <b>Heterogeneity</b>           | Low                  | High     | High     | High                       | Low                        |
| <b>Security</b>                | Low                  | High     | High     | Low                        | Low                        |
| <b>Scalability</b>             | High                 | High     | High     | Low                        | Low                        |

**Table 2. 1 Requirements and common characteristics of wireless ad hoc networks**

All mentioned networks use wireless communication mechanisms. Communication mechanisms of WSN might classify in four categories: molecular (or chemical), electromagnetic, nanomechanical and acoustic. These communication mechanisms are described in section 2.8 of the chapter. Devices of WSN and WNSN are supposed to be small sized, based on this fact, the data storage of these devices are very low. In case of MANET and VANET, as mentioned before, devices have higher computational and data storage abilities.

Security in WSN, WNSN, MANET and VANET is an open research issue. When it comes to MANET and VANET, devices move in open areas, and exchanged information might be accessed. WNSN are initially designed to be deployed in closed areas, such as human or animal body, and data security is not a major concern.

In addition to the security issue, scalability is an important issue that needs to be addressed when designing these networks. For example, some wireless ad hoc networks

could contain of hundreds or thousands of members. Therefore, the protocols and routing techniques for this type of networks should function effectively when network contains large number of stations. Typical WSN could contain hundreds or even more members. Thus, the scalability should be considered in forming stage of WSNs.

However, several issues need to be addressed to deploy WNSN applications. For example, physical and practical limitations of nanodevices should be taken into consideration in the development of communication techniques between nanodevices. In the implementation process of WNSN, an interface that performs interconnection between nano world and micro world should be realized. The rest of this document is dedicated to existing work related to WNSN communication mechanisms.

### **2.3 An overview of Nanonetworking communication mechanisms**

Nanocommunication networks are communication networks that exist at the nanometer scale. Nanodevices can be connected with each other to perform common tasks in a distributed manner and obtained network is envisaged to expand the capabilities and applications of single nanodevices. Nanodevices such as chemical sensors, nano-valves, nano-switches, or molecular elevators, cannot execute complex tasks by themselves [6]. Data exchange and commands among nanodevices enables them to work together and synchronously to execute difficult tasks such as drug delivery or indicate analysis of blood in human organism. Thus, using nanocommunication enables larger application scenarios, such as monitoring and control of chemical agents in ambient air. WNSN enables the interaction with remote nanodevice through nanocommunication mechanisms. The rest of this section presents these mechanisms together with the transmission process.

### ***2.3.1 Nanocommunication mechanisms***

Nanocommunication might be classified into four categories: electromagnetic, molecular (chemical), nanomechanical and acoustic communication mechanisms [6].

Acoustic communication method uses acoustic energy for transmitting and receiving messages, and messages could be encoded using pressure variations. Acoustic communication is mostly based on the transmission of ultrasonic waves in nanoscale. The acoustic communication implies the integration of ultrasonic converters in the nanodevices. These converters should be able to sense the changes of pressure produced by ultrasonic waves and to emit acoustic signals. The propagation speed in WNSN designed using electromagnetic and acoustic communication method is much faster than the propagation of molecular messages [37] [38].

Nanomechanical communications defined as the transmission of information through mechanical contact between the transmitter and the receiver, i.e., information flows through the mechanical connection of nanodevices. Molecular communication based WNSN use molecules and their components, such as gap junctions, receptors, nucleus, etc. [38]. Molecular communication between nanoscales entities occur in nature, it explains why using molecular communication is particularly useful. Besides, there is a several advantages designing WNSN based on molecular communication, such as biocompatibility, biostability, etc. [6].

Electromagnetic radiation based communication is rapidly gaining the attention of the scientific community. In fact, it is already possible to exploit some features of nanomaterials for performing, at the nanoscale, the transmission and the process of electromagnetic signals. The research on this type of WNSN is still at an early phase and

a number of critical issues have to be faced before a spread adoption of such a technology in biomedical, industrial, and military domains [35].

The latest achievements in molecular and carbon electronics area have enabled the development of novel nano sized components, such as nanobatteries, nanoantennas, nanomemory, and logic circuits in the nanoscale. From a communication perspective, the unique properties observed in novel nanomaterials will decide on the specific bandwidths for emission of electromagnetic radiation, the time lag of the emission, or the magnitude of the emitted power for a given input energy. All these require a fundamental change in the current state of the art of analytical channel models, network architectures and communication protocols [35].

It is worth noting that Terahertz Band (0.1-10 THz) communication might allow for designing EM-based WNSN. Terahertz Band communication depends on molecular composition of the medium and transmission range. For a transmission range in the order of several tens of millimeters, the Terahertz band can be considered as a single transmission window almost 10 THz wide. This is the main difference with existing Terahertz communications systems, which are focused on using a single transmission window below 350 GHz [2].

In WNSN, nanoantennas perform radiation and reception processes in nanoscale, they might have several nanometers wide and few micrometers long. Moreover, nanoantennas should be easily integrated in nanodevices. In the development of nanoantennas, using Carbon Nanotubes (CNTs) and Graphene Nanoribbons (GNRs) could be effective method. In the modeling of nanoantennas based on nanotubes and nanoribbons the specific operating range, the bandwidth radiation, and efficiency of radiation should be

taken into consideration. CNTs and GNRs determine the communication capabilities of nanodevices [35].

Nanoantennas should easily integrated in nanodevices. In the development of nanoantennas, using Carbon Nanotubes (CNTs) and Graphene Nanoribbons (GNRs) could be effective method.

CNTs have a variety of shapes, they can be large or small, single-layer and multi-layer, straight and spiral. They are very strong in tension and bending. Moreover, CNTs have extraordinary mechanical, electronic and optical properties. For example, depending on the special scheme folding plane graphite, nanotubes can be conductors and semiconductors. In nature, there is no other material having such a simple chemical composition and many useful properties (figure 2.7).

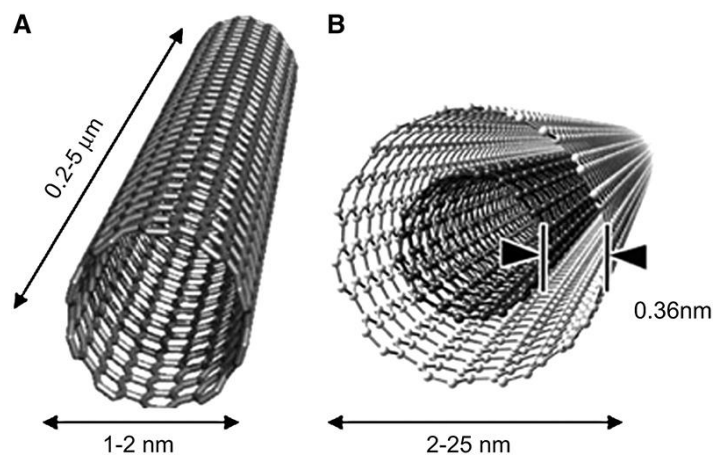


Figure 2. 6 Carbon Nanotubes [41]

### 2.3.2 Transmission process in nanoscale

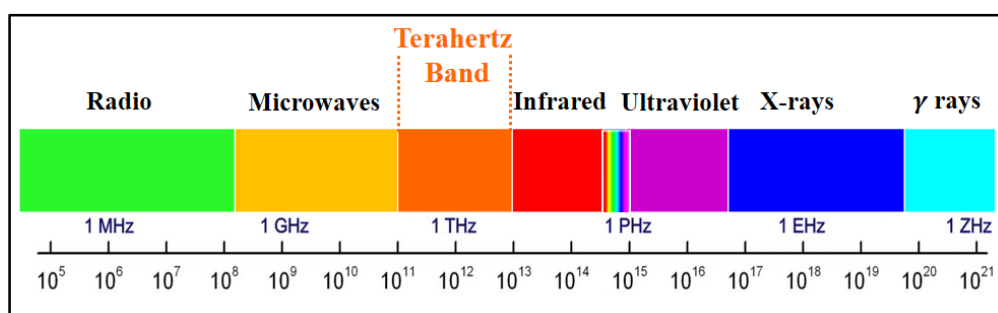
Transmission is the disseminating a digital signal over a physical channel (i.e. wired, wireless or optical fiber) as data packets in a network. The data should be converted to radiowave, microwave, or infrared signal. The transmission process is directly connected to the physical layer of a network (modulation and demodulation scheme, line coding,

equalization, error control, bit synchronization and multiplexing). Transmission process occurs among nanoscale nodes in nanonetworks. The data should be converted as signals in Terahertz Band (THz).

Terahertz Band (0.1-10 THz) communication might allow for designing networks in nanoscale. Terahertz band is between infrared and microwave radiation in the electromagnetic spectrum (Figure 2.6). Therefore, this band might present some characteristics of neighboring radiations, i.e. terahertz radiation travels in a line of sight and is non-ionizing, and it can penetrate a wide variety of non-conducting materials. In fact, terahertz waves can be transmitted through materials, such as plastic and wood to enable analysis of their internal structure.

The main absorber of terahertz waves is the atmosphere of earth and about 10 meters might be useful for designing high bandwidth wireless networks (nanonetworks). Terahertz Band communication channel is depends on molecular composition of the medium and transmission distance. The main factor affecting the behavior of the Terahertz Band is the absorption by water vapor molecules, which does not only attenuate the transmitted signal, but it also introduces colored noise. In the very short range, i.e., for a transmission distance in the order of several tens of millimeters, the Terahertz Band can be considered as a single transmission window almost 10 THz wide. This is the main difference with existing Terahertz communications systems which are focused on utilizing a single transmission window below 350 GHz. The very high channel capacity of the Terahertz Band does not only support very high transmission bit-rates, but it also enables new information encoding and modulation techniques as well as novel networking protocols more suited for resource limited nanodevices [2].

Terahertz Band communication facilitates the spectrum scarcity problem and overcome the capacity limitations of current wireless systems, and enable new applications both in classical networking domains as well as in novel nanoscale communication paradigms. While the frequency regions immediately below and above this band (the microwaves and the far infrared, respectively) have been extensively investigated, this is still one of the least-explored frequency ranges for communication. Therefore, there are many issues in this field, such as new solid-state graphene-based transceivers, graphene-based ultra-broadband antennas, channel propagation models, novel solutions for the physical layer and link layer functionalities [39].



**Figure 2. 7 Terahertz Band (0.1 - 10 THz) in the Electromagnetic Spectrum**

Any data, which is the object of transfer, distribution, conversion, storage and use, is an information. The message is the presentation of information. It could be text, sound pressure, brightness, color, etc. An operator or a technical devices that convert information into a signal and vice versa, could be source (or destination) of information. Message is an electrical signal (current or voltage) when used radio technical means. Information (and consequently, message) is a slowly varying function of time and location. These radio waves are carrier signals. The radio waves used for better transmission of information over long distance. The other name of these radio waves is carrier signals. A carrier signal is a waveform (usually sinusoidal) that is modulated

(modified) with an input signal for conveying information. This carrier wave is usually a much higher frequency than the input signal. The purpose of the carrier is usually either to transmit the information through space as an electromagnetic wave (as in radio communication), or to allow several carriers at different frequencies to share a common physical transmission medium by frequency division multiplexing (as, for example, a cable television system). Modulation is the process of transferring messages on a carrier signal. Message is a radio signal in the modulation. The message will be received again in the receiver of the communication system. This process called as demodulation or detection.

Depending on the function which describes the signal parameters, signal classification can be divided as the following:

- analog;
- discrete;
- quantized;
- digital.

A digital signal is a physical signal. It is a conversion of a sequence of discrete values (bit stream or digitized analog signal). The term digital signal can refer to either of the following:

- any continuous-time waveform signal used in digital communication, representing a bit stream or other sequence of discrete values;
- a pulse train signal that switches between a discrete number of voltage levels or levels of light intensity, also known as a line coded signal or baseband transmission.



As mentioned before, communication among nanodevices occurs Terahertz Band signals. Authors of [40] model the generated signals as one hundred-femtosecond-long Gaussian pulses. The power spectral density of these pulses has its main frequency components in the Terahertz Band. An additional technology limitation at the generator is that pulses cannot be transmitted in a burst, but due to the relaxation time of SPP waves in the HEMT channel, need to be spread in time. In our analysis, we consider the energy per pulse and the spreading between pulses as two technology parameters.

Electromagnetic (EM) based communication among nanonodes cannot be implemented with reduction of classical antenna size. CNTs support surface Plasmon Polaritons; nanoantennas might be implemented using this property. Surface plasmons (SPs) are coherent delocalized electron oscillations that exist at the interface between any two materials where the real part of the dielectric function changes sign across the interface (e.g. a metal-dielectric interface, such as a metal sheet in air). SPs have lower energy than bulk (or volume) plasmons, which quantize the longitudinal electron oscillations about positive ion cores within the bulk of an electron gas (or plasma). The dimensions of nano-antennas, designed based on CNTs might be a few nanometers. It resonates in the terahertz band, at a dramatically lower frequency and with a higher radiation efficiency. CNTs-based nano-antennas are envisaged to enable wireless communications among nanosystems.

In the modeling of nanoantennas based on nanotubes and nanoribbons should be taken account the specific operating range, the bandwidth radiation and efficiency of radiation. All these will determine the communication capabilities of nanosensor devices [35].

Electromagnetic waves are the propagation of electromagnetic fields in space and time; they arise by the vibration of an electric charge and have an electric and a magnetic

property. An electromagnetic wave transports its energy through a vacuum at a speed of  $3.00 \times 10^8$  m/s (a speed value commonly represented by the symbol  $c$ ). The propagation of an electromagnetic wave through a material medium occurs at a net speed, which is less than  $3.00 \times 10^8$  m/s.

In the energy transfer through the material, atoms absorb and reemit the wave energy. Energy absorption occurs because of the electrons within the atoms to undergo vibrations. Vibrating electrons create a new electromagnetic wave with the same frequency as the first electromagnetic wave after a short period of oscillatory motion. Movement of electromagnetic waves is delayed in the environment for a very short time during oscillation. Once an atom re-emits the energy of the electromagnetic wave, it travels through a small region of space between atoms. Once it reaches the next atom, the electromagnetic wave is absorbed, transformed into electron vibrations and then reemitted as an electromagnetic wave. While the electromagnetic wave will travel at a speed of  $c$  ( $3.00 \times 10^8$  m/s) through the vacuum of interatomic space, the absorption and reemission process causes the net speed of the electromagnetic wave to be less than  $c$ .

The actual speed of an electromagnetic wave through a material medium is dependent upon the optical density of that medium. Different materials cause a different amount of delay due to the absorption and reemission process. Furthermore, different materials have their atoms more closely packed and thus the amount of distance between atoms is less. These two factors are dependent upon the nature of the material through which the electromagnetic wave is traveling. As a result, the speed of an electromagnetic wave is dependent upon the material through which it is traveling [42].

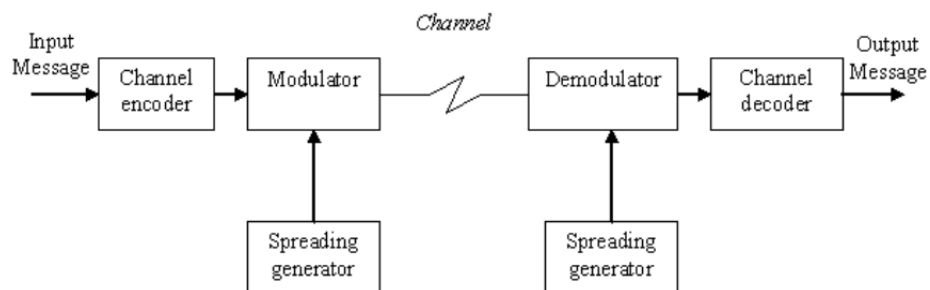
The research on EM-based communication is in its early stage, although this direction of research is rapidly gaining the attention of scientific community [35] [43] [44] [2] [45].

There are many issues, which should be solved. For instance, it is very important to create theoretical and practical aspects for forming nanodevices and connection methods among them.

Graphene-based EM nano-transceivers will operate in the Terahertz Band, the frequency range in the EM spectrum that spans the frequencies between 0.1 to 10 THz. While the frequency regions immediately below and above this band (the microwaves and the far infrared, respectively) have been extensively investigated, this is still one of the least-explored zones of the EM spectrum.

### 2.3.3 Spread Spectrum

Frequency dependent fading can wipe out narrow band signals for duration of the interference. This is the main issue of radio transmission. For solution of the issue suggested spreading the narrow band signal into a broadband signal using a special code. Spread Spectrum is a mechanism of the data transmission process. Independently of transmission data, this mechanism uses a pseudo-noise code. A pseudo-noise code is used as a modulation waveform to “spread” the signal energy over a bandwidth much greater than the signal information bandwidth. At the receiver, the information signal is “despread” using a synchronized replica of the pseudo-noise code (Figure 2.8).

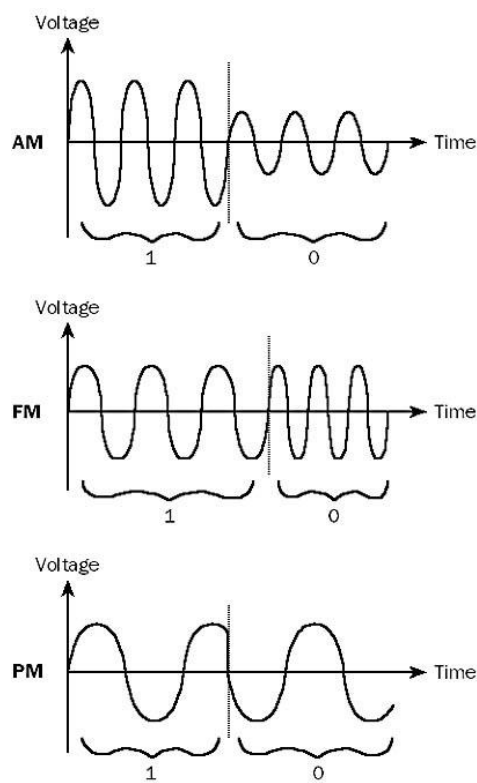


**Figure 2. 8 Spread spectrum communication system**

The spread spectrum have two main techniques:

- Frequency hopping (FH), which makes the narrow band signal jump in random narrow bands within a larger bandwidth.
- Direct sequence (DS) which introduces rapid phase transition to the data to make it larger in bandwidth.

In the modulation process, binary information should be converted into analogue or electrical signals for transmission over the medium. Modulation forms the basis of the digital-to-analog converter (DAC) component of an analog modem. Modulation in modems allows digital binary information to be received from a serial interface on a computer and modulated for transmission over the voice-grade PSTN telephone network.



**Figure 2. 9 Different types of modulation**

Three types of signal modulation for analog signals can be used (Figure 2.9):

*Amplitude modulation (AM)*: carries information by modulating the amplitude (voltage) of the carrier signal. Different amplitudes represent different information values. For example, an amplitude of 3 volts might represent a 1, while an amplitude of 1 volt represents a 0.

*Frequency modulation (FM)*: carries information by modulating the frequency of the carrier signal. Different frequencies represent different information values. For example, a frequency of  $f$  might represent a 1, while a frequency of  $2f$  represents a 0. A common frequency modulation scheme in modem technologies is called frequency-shift keying (FSK), in which four frequencies within the PSTN 3-KHz line bandwidth are used for transmission and reception of binary data, as shown in the following table.

| <b>FSK Frequency</b> | <b>Meaning</b>         |
|----------------------|------------------------|
| 1070 Hz              | Transmitted binary – 1 |
| 1270 Hz              | Transmitted binary – 0 |
| 2025 Hz              | Received binary – 0    |
| 2225 Hz              | Received binary – 1    |

**Table 2. 2 Frequencies Used in FSK Modulation**

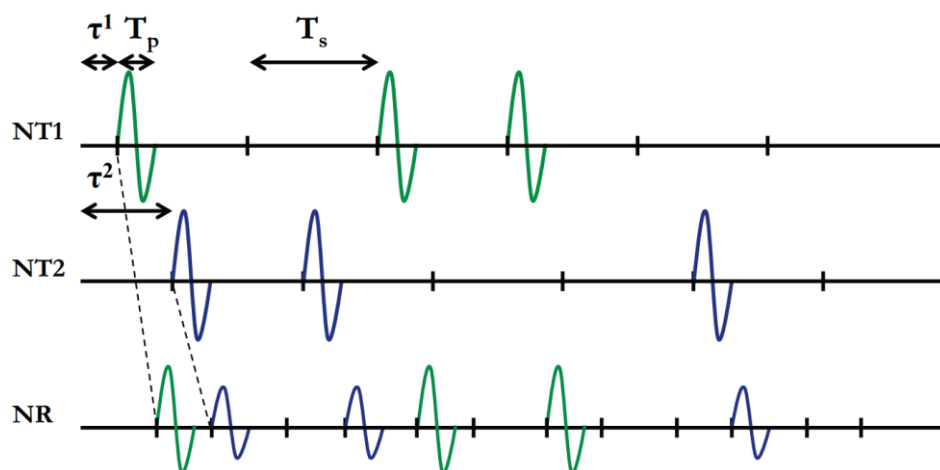
*Phase modulation (PM)*: Carries information by modulating the phase of the carrier signal. Different phases represent different information values. For example, a phase of  $0^\circ$  might represent a 1, while a phase of  $180^\circ$  represents a 0. A common implementation of phase modulation in modem technologies is called differential phase-shift keying (DPSK), in which relative phase changes instead of absolute phase values are used to represent encoded binary information. Quadrature amplitude modulation (QAM) allows the encoding of pairs of binary values as different phase values, as shown in the following table.

In light of the capabilities of nano-transceivers, we propose the use of TS-OOK for communication among nano-devices in the Terahertz Band. TS-OOK is based on the exchange of one-hundred-femtosecond-long pulses among nano-devices. The functioning of this communication scheme is as follows [40]:

- A logical “1” is transmitted by using a one-hundred femtosecond-long pulse and a logical “0” is transmitted as silence, i.e., the nano-device remains silent when a logical zero is transmitted. As discussed above, solid-state Terahertz Band transceivers are not expected to be able to accurately control the shape or phase of the transmitted pulses and, thus, a simple OOK modulation is used. To avoid the confusion between the transmission of silence and the no transmission, initialization preambles and constant-length packets can be used. After the detection of the preamble, silence is considered a logical “0”.
- The time between transmissions is fixed and much longer than the pulse duration. Due to the nano-transceiver limitations above described, pulses or silences are not transmitted in a burst, but spread in time as in IR-UWB. By fixing the time between consecutive transmissions, after an initialization preamble, a nano-device does not need to continuously sense the channel, but it just waits for the next transmission. This scheme does not require tight synchronization among nano-devices all the time, but only selected nano-devices will be synchronized after the detection of the initialization preamble.

An example of TS-OOK for the case in which two nanodevices are simultaneously transmitting different binary sequences to a third nano-device illustrated in Figure 2.10. The upper plot corresponds to the sequence “101100”, which is transmitted by the first nano-device. A logical “1” is represented by the first derivative of a Gaussian pulse and

a logical “0” is represented by silence. The time between symbols is  $T_s$  is very small for a real case but convenient for illustration purposes. This signal is propagated through the channel (thus, distorted and delayed). Similarly, the second plot shows the sequence transmitted by the second nano-device, “110010”. This second transmitter is farther from the receiver than the first transmitter.



**Figure 2. 10 TS-OOK illustration: top) First nano-device transmitting the sequence “101100”; middle) Second nano-device transmitting the sequence “110010”; bottom) Overlapped sequences at the receiver side [40].**

### 2.3.4 Transmission power

In the design of wireless ad hoc and sensor networks considering power conservation is most important issue, since the lifetime of nodes rely on battery power. With prolonging lifetime of nodes, the life of a whole network is also extended. Transmitting at unnecessarily high power not only reduces the lifetime of the nodes and the network, but also introduces excessive interference. If the power of transmission is too small, the network might be disconnected.

Radio Frequency (RF) transmitters are essential part of a wireless communication. For example, cell phones, radar, military communications, wireless local area networks,

modems, signal generators and systems that apply one or more transmitters. Productivity of a transmitter and quality of signal is determined by the operational parameters and design considerations. Providing transmitter with good technical specifications guarantees required quality of communication.

The most common RF transmitter measurement is RF power. Depending on the design and application of RF transmitter, measuring RF power takes various forms. RF output may be a simple continuous wave (CW) signal, a pulse, analog modulated signal, or a complex digitally modulated transmission. The power measurement can be averaged across a time period, such as across a series of RF pulses, yielding the average power. RF power can be integrated over a frequency band, as is the case for many mobile communication signals. Digitally modulated signals tend to be noise-like in nature and often have specified average and peak power values [46].

Measuring RF power of a CW is the simplest method of measuring RF power.

One accurate and cost-effective instrument for measuring RF power is the RF power meter. Because it's a scalar instrument, incapable of measuring phase, care should be taken to minimize impedance mismatches whose reflections can add in and out of phase with the signal being measured, resulting in greater magnitude uncertainty. Power meters are broadband and not frequency selective, so any unwanted signals are averaged into the desired measurement. The dynamic range of most power meters is 50 to 70 dB. High-end power meters are capable of specialized measurements such as integrated power across a band and triggering for pulsed RF power. For these reasons, power meters are a good choice if the RF environment is well controlled.



Another instrument commonly used to measure RF power is a spectrum analyzer. With these more complex RF instruments, engineers can measure the individual spectral components across frequency. The absolute power measurement accuracy is not outstanding, typically + 0.5 to + 2.0 dB. However, the relative power accuracy (or amplitude linearity) is excellent. Therefore, calibrating at a given frequency with a known power level, from a signal generator, for example, results in corrected power measurements that are accurate across a dynamic range greater than 100 dB.

High-performance RF instruments, including vector signal analyzers and vector network analyzers, can measure magnitude and phase, offering the potential for greater error correction and measurement accuracy. In addition to the RF power measurements mentioned previously, specialty measurements can be made on pulsed and other complex RF waveforms. This includes pulse profiling, which measures the power across the envelope of an RF pulse, along with the average and peak power of the RF pulse. Complex IQ waveforms are measured in more of a noise-like fashion with measurements such as peak-to-average ratio, and complementary cumulative distribution function (CCDF).

One final consideration when measuring RF power is measurement speed. Power meters offer excellent accuracy but typically slower measurement times with respect to high-performance RF instruments. This frequent trade-off between accuracy and speed is a compromise that can be mitigated to some extent with enhanced calibration procedures. Understanding the type of RF power measurement, the accuracies required, and the capabilities of the RF instrument will result in accurate repeatable measurements [47].

To improve spectral efficiency and permit multiple users for a given spectrum, RF transmitters use a variety of modulation techniques to encode and send information. Modern communications are allocated a specific amount of frequency spectrum, often

referred to as a “channel.” The channel is usually defined by a regulating body, such as the Federal Communications Commission (FCC) in the United States. Users are generally concerned with two measurements with regard to their assigned spectrum. One measurement is the integrated power across the assigned channel, often called the occupied bandwidth (OBW), power-in-band, or channel power. Here the power is integrated across the channel from the assigned start to the assigned stop frequency.

In addition to measuring the power in the channel, there is also a need to ensure that transmissions are not leaking into channels assigned to other users, especially those on either side of the assigned channel. In addition to technical shortcomings, this can result in costly fines from regulatory agencies. A typical test approach is to fill the assigned (occupied) band with a test signal and measure the integrated power versus frequency in the channels adjacent to the occupied channel. This test goes by many names, but it’s generically referred to as the adjacent channel power (ACP) measurement. The exact frequencies, integrated power specifications, and test methods are specified by the standards governing the transmission [46].

## **2.4 WNSN for embedded system design**

In parallel to this progress, industry is reaching limits regarding the speed of processors that can be placed in an on-chip system with low power consumption and heat dissipation. In other words, embedded computing systems have become widespread in various application domains, as evident from their use in products such as PDAs, household appliances, telecommunication, and automotive systems. This has been further accelerated by the advances in silicon technology, which had led to the design of complex and large SoCs. More precisely, rapid advances in technology and design tools enabled

engineers to design SoC with hundreds of cores. These systems are composed of several processing elements (PEs), dedicated hardware and software components that are interconnected by a Network-on-Chip (NoC). According to Moore's law, the number of cores on-chip will double every 18 months, and therefore thousands-cores on-chip will be integrated in the next 20 years in order to meet the power and performance requirements of applications. The future and current tendency goes to the integration of more and more cores in a single chip. A key element in the performance and energy consumption in SoCs is the NoC infrastructure [48]. More precisely, while microchip technology miniaturized and gates become faster and more energy efficient, wires used for communication between cores are performing slowly and more energy hungry. Therefore, NoC infrastructure represents one of most important component that determines the overall performance (e.g., latency and throughput), reliability, and cost (e.g., energy consumption and area overhead) of future SoC [49].

Recently, Radio Frequency (RF)/Wireless NoC, 3D NoC, photonic NoC have been introduced to alleviate these problems by, for example, replacing some of the multi-hop wire links with high-bandwidth single-hop long-range wireless channels [50]. Several studies have shown that wireless NoCs are promising alternatives to conventional OCIs (On-chip Interconnects), which allow reducing latency and energy dissipation in communication between remote nodes. Other studies show that nanophotonic communication are expected to reach levels of performance-per-watt scaling by supporting energy-efficient high-bandwidth data transfers among processing cores. In [51], authors have stated clearly that 3DNoC, nanophotonic communication and on-chip wireless links are all promising alternatives to traditional interconnects for building on-chip interconnects of future multi-core systems-on-chip.

The advantages of Nano-NoC-based architectures include high scalability, low latency, high bandwidth, distributed routing decisions and low energy consumption.

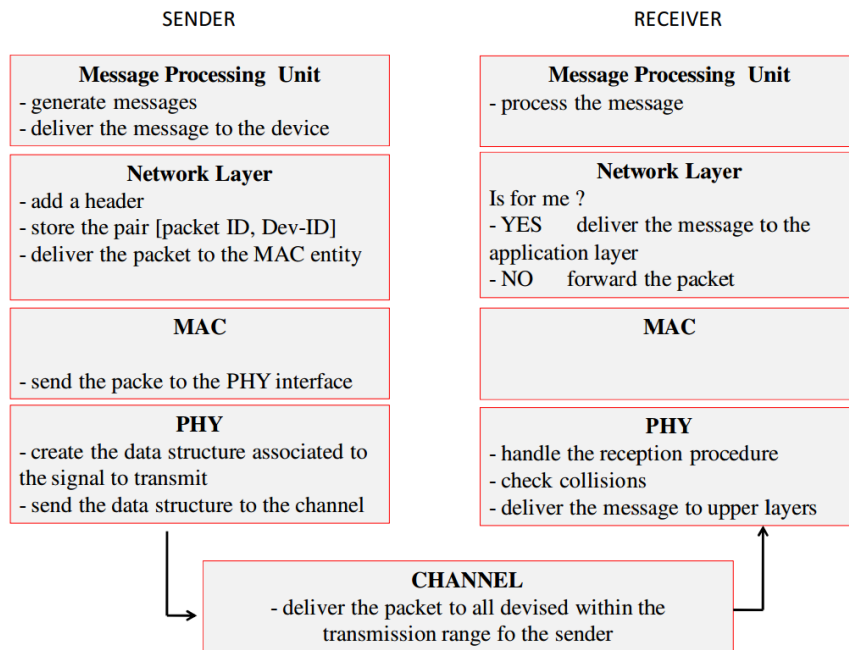
## 2.5 Simulation tools for nanonetworks

Designing and developing set of protocols for EM-based WSNs might accelerate implementing WSNs. The simulators helps to develop routing and MAC protocols for WSNs. Currently available tools [52] [43] [44] support molecular- and EM-based approaches. Within of this thesis, we have used upgradeable simulation platform, intended for wireless nanosensor networks based on electromagnetic communication in the terahertz band.

Currently available tools, such as NanoNS [53], N3Sim [52] have been explicitly conceived for diffusion-based molecular communications. We have used Nano-Sim to study WSNs that uses EM waves in the terahertz band [43] [44]. Nano-Sim is an open source simulator, which is implemented in the Network Simulator 3 (NS3). NS3 is a discrete-event network simulator, targeted primarily for research and educational use. It is free software, licensed under the GNU GPLv2 license, and is publicly available for research, development, and use [54]. The main features covered by the developed Nano-Sim tool are (Figure 2.11):

- The implementation of different devices forming a WSN;
- A physical interface based on the Time Spread On-Off Keying (TS-OOK) modulation scheme;
- A simple Media Access Control (MAC) protocol;
- A routing module based on the flooding strategy;
- A generic unit for generating and processing messages.

A scalability study on the computational requirements (i.e., simulation time and memory usage) of Nano-Sim has been provided, showing that, as obviously expected, the simulation time increases with the number of nanomachines, but the memory usage remains limited also in scenarios with a high traffic load.



**Figure 2. 11 Network architecture entailed by Nano-Sim [44]**

While investigating WNSN using NanoSim we have highlighted several issues that need to be considered:

- Designing nanodevice
- Architecture of WNSN
- Communication methods in terahertz band

In the thesis, we have concentrated our effort mainly to investigate and study communication methods. Thus, we present following problems and we have proposed solutions in other chapters. Whereas we are investigating EM-based WNSNs, the

dissemination information is envisioned as one of the main issue we talked in the beginning of our work. It is worth noting that flooding is a core protocol to disseminate data among nodes and also it is very costly in terms of wasted bandwidth. Therefore, reducing redundant transmissions is one of our primary focus.

By modifying some parameters of the flooding mechanism collisions and energy consumption are minimized by reducing the number of rebroadcasting. For example, storm problems are presented in [55] [56] and several useful recommendations and algorithms are presented. Generally, algorithms that reduce transmissions are based on node's geometrical or topological status. Transmission range is also another issue that should be tackled. Due to high transmission range, collisions and redundant transmissions has been observed during our preliminary investigations. Short transmission range is also a cause of disconnected nodes. Therefore, transmission range should be tuned up carefully according to the network density.

Networks-on-Chip (NoCs) paradigm has been proposed as the best scalable communication infrastructure for Multi-Processor System-on-Chip (MP-SoC) designs [57]. The main objectives are to satisfy the quality of service, to optimize the resources usage and to minimize the energy consumption by separating the on-chip communication (OCI) from the computation [50] [58] [59]. Recently, Radio Frequency (RF)/Wireless NoC, 3D NoC, photonic NoC have been introduced to alleviate these problems by, for example, replacing some of the multi-hop wire links with high-bandwidth single-hop long-range wireless channels [50] [60]. Several studies have shown that wireless NoCs are promising alternatives to conventional OCIs, which allow reducing the latency and the energy dissipation in communication between remote processing elements (PEs).

## 2.6 Summary and discussion

Nanotechnology is one of the fields of fundamental sciences and applied technologies that enables the design and engineering of miniaturized nanodevices in a scale of few nanometers. These nanodevices are tiny devices that perform sensing and very simple computation tasks. Alike other wireless ad hoc networks, these machines could be interconnected in order to increase their capabilities and then execute collaborative tasks in a distributed manner. Several applications, ranging from biomedical, environmental, industrial, to military services, could benefit from this new communication paradigm. For example, the largest number of applications of WNSN is in the biomedical field.

WNSN could be also used in industries to help developing new quality control procedures and manufacturing processes. These applications have been proposed to improve systems of controlling quality of food and water, materials and fabrics. However, research in EM-based WNSN is not mature yet. Especially, analytical performance evaluation and simulation tools are required to study new protocols and standards. Furthermore, new cost-effective solutions are required for communication among thousands of distributed nanodevices. For example, adaptive transmitting range for high connectivity and energy consumption reduction is one of the most important problems in EM-based WNSN. The goal is to determine the adaptive transmission range for connectivity, i.e., the minimum value for transmission range, which generates communication graphs that are connected with a high probability. Several adaptive techniques have been proposed in the context of ad hoc networks (e.g., MANET, WSN, VANET) and could be also adapted in EM-based WNSN by considering limited capabilities of nanodevices.

In summary, these networks should scale and reach acceptable level of performance in terms of throughput and latency with little overhead (e.g., energy consumption) even when large number of nodes has to be deployed. Furthermore, since these networks do not rely on any fixed infrastructure and nodes should relay messages, energy-efficient protocols are required. Due to dynamic nature of these networks, adaptive approaches and protocols are required and still an open research issue.

Furthermore, approaches aiming at investigating EM-based WNSN mechanisms as an on-chip communication fabric for high-performance SoC design are required. Especially, new techniques in modeling, design, and simulation of NoC at nanoscale are of most importance. While several challenges have to be addressed, efficient design of Nano-on-Chip communication techniques may offer a unique solution for high-performance SoC design. This could provide new opportunities for lowering power computing which can be deployed in portable embedded devices and sensors.



## Chapter 3: Efficient flooding algorithm

The major contribution of this chapter is a comprehensive introduction of main concepts and communication protocols. First, we will talk about communication broadcasting by flooding mechanism, followed by classification of information dissemination approaches in wireless networks. Then we propose efficient flooding algorithm for information dissemination. Finally, we present simulation results to observe nanonetwork behavior.

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### 3.1 Broadcasting mechanism

Broadcasting is widely used in wireless networks to resolve many issues. It is a data transferring method in wireless networks. All neighboring nodes of transmitter will receive broadcasted data. Generally, when it comes to WNSNs, nanonodes supposed to be move freely in the environment, consequently, could arise some difficulties in delivering a data from transmitter to receiver. Moreover, WNSNs has no infrastructure and the higher mobility of the nanonodes, relaying messages between nanonodes require broadcasting schemes. Due to limitations (such as tiny size, scarce memory, energy) nanonodes are not able to communicate with destination node by single-hop scenario. The main problem in multi-hop scenario is the excessive rebroadcasts. Reducing rebroadcasts allows saving energy and minimizing data collisions, while maintaining good throughput and acceptable latency.

In flooding mechanism, several intermediate nodes will act as relay between source and destination nodes. In this scenario, intermediate nodes might receive same message several times (Figure 3.1). Usually, flooding will be performed after short time slot to decrease message collisions. The disadvantages of flooding mechanism are listed below:

- Flooding mechanism is a costly concerning air interface usage.
- It is unreliable in terms of duplicating messages; duplicating is a cause of collision, since some nodes might rebroadcast same message at the same time.
- It requires high-energy consumption due to excessive rebroadcasting.

Consequently, modifying some parameters of flooding mechanism becomes necessary in order to minimize collisions and energy consumption by reducing the number of

rebroadcasting. It is important to note that modifications should not significantly affect main metrics, such as latency and throughput.

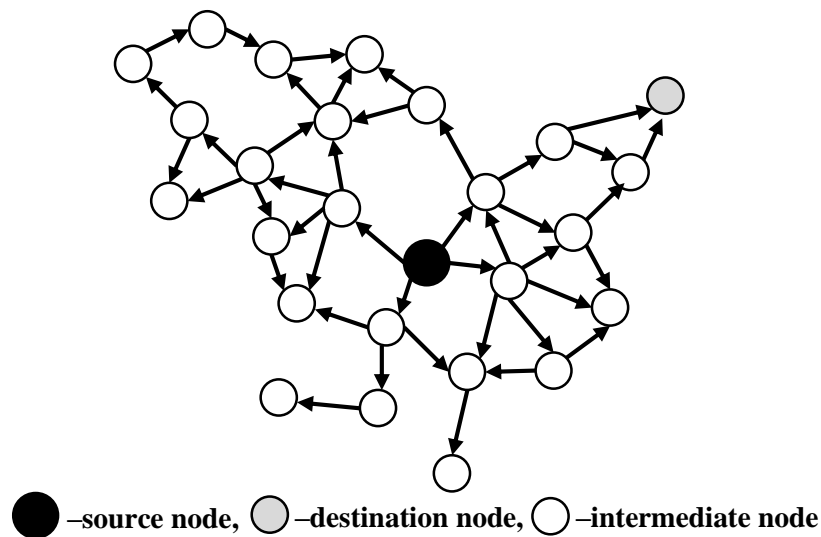
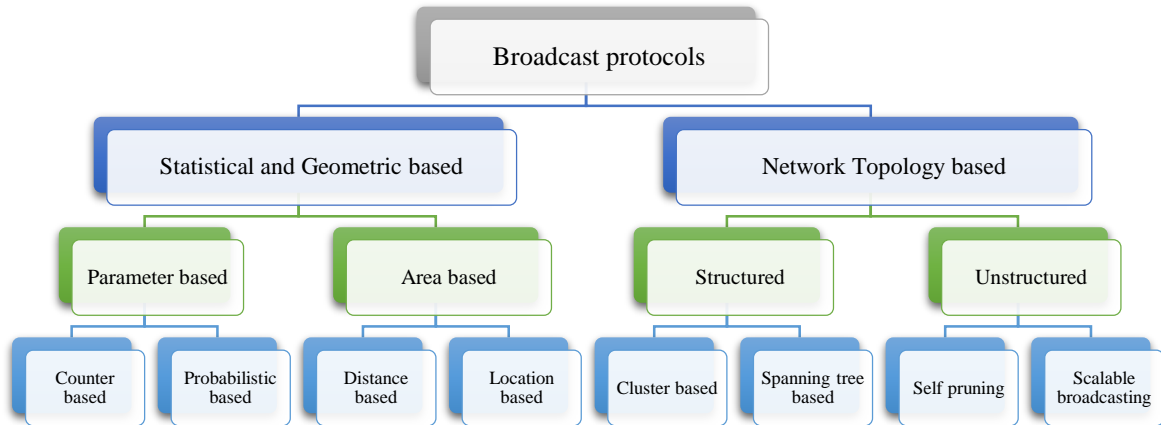


Figure 3. 1 Broadcasting by flooding problem

The flooding algorithm has been modified by using certain free parameters to reduce the number of redundantly received messages. The core problem is finding a way to minimize the number of redundantly received messages in order to save transmission energy while, at the same time, maintaining good latency and packet delivery ratio. Therefore, the selection of relay nodes is a major design consideration in all broadcasting algorithms [61] [55] [62]. All algorithms differ in how a node estimates redundancy and how it accumulates knowledge to assist rebroadcasting decision, i.e., rebroadcast and discard the message. Protocols proposed in literature might be categorized as geometric-based (or statistical) and network topology-based protocols.

The first category is based on thresholds such as distance, counting redundant messages, etc. The main goal of this category is to estimate the network density. Network topology-based protocols are based on complex structures or information about

neighborhood for constructing broadcasting schedule. Protocol categories presented in Figure 3.2.



**Figure 3. 2 The classification of broadcasting protocols [63]**

### ***3.1.1 Geometric Based Protocols***

Geometric-based protocols divided into two groups: parameter-based and area-based.

The parameter-based protocols extend the flooding technique [64] [65]. Briefly, the main function of these protocols might be described as following: if a message is seen for the first time by an intermediate node, the message will be rebroadcasted to nodes that located inside transmission range of the intermediate node.

One of these mechanisms is counter-based scheme for broadcasting. The principle of this algorithm is as follows: a message will be rebroadcasted only if the number of received copies at a host is less than a threshold after random delay time (RDT) [65] [55] [56]. In [66], authors have modified the counter-based protocol and named the new protocol as Hop Count Ad hoc Broadcasting (HCAB) protocol. In HCAB, upon receiving a broadcast message for the first time, the node initiates a flag  $R = \text{true}$  and records initial hop count value  $HC_0$  of this message. Meanwhile, this node sets a RDT value between 0

and  $T_{max}$ . During the RDT, the node compares the hop count of redundantly received message  $HC_x$  with  $HC_0$  and flag  $R$  is set to false if  $HC_x > HC_0$ . When the random delay expires, the node will relay this message if  $R$  is true. Otherwise, it just drops this message. The counter based techniques rely only on fixed counter  $HC_0$  and also the message delay at each hop is increased due to RDT and counter comparison.

In the probabilistic technique, intermediate nodes rebroadcast messages according to certain threshold randomly selected. This scheme definitely reduces excess rebroadcasts, but its performance suffers in less dense networks. In dense networks, multiple nodes share similar transmission coverage, and therefore some nodes doesn't need to retransmit (the threshold need to be low), and in sparse networks, there is much less shared coverage, some nodes have to retransmit (the threshold needs to be high).

Area-based technique broadcasting uses geographical location of transmitter to choose an additional transmission range [67]. Distance-based and location-based schemes are main approaches of this category. Only a neighbor, which is located farthest from a transmitter, rebroadcasts the message in the distance-based scheme [55]. After receiving a previously unseen message, a RDT, that chosen between 0 and  $T_{max}$  seconds, is initiated and redundant messages will be cached. When the RDT is expired, all source node locations are examined to see if the node is closer than a threshold distance value. If true, the node does not rebroadcast.

In the location-based scheme, another method applied for calculation of expected additional transmission range. According to the rules of this method, geographical location of the transmitter will be attached as an additional information to the message. Upon receiving a message, an intermediate node computes the additional transmission range using location of the transmitter. If the additional area is less than a threshold, the

intermediate node does not rebroadcast the message, other receptions of the message will be rejected. Otherwise, a node assigns a RDT before rebroadcast. If an intermediate node receives the same message during a RDT, it calculates the additional transmission range and compares it with the threshold. The process continues until the message finally rebroadcasted or rejected. The disadvantage of this scheme is that it assumes that the nodes are equipped with a GPS receiver. Moreover, area-based methods also presume that visibility can be estimated merely from the position of the nodes i.e. it mainly depends upon the distance of the nodes. This is realistic only if there is no shading objects, e.g., users are in a plain field. Finally, the distance calculation also increases the computational overhead that ultimately cause increases broadcast latency.

### ***3.1.2 Network topology-based protocols***

The network topology-based protocols are also subcategorized in structured and unstructured protocols. Unstructured protocols use information about neighboring nodes to compute an additional number of nodes as broadcast recipients. Structured protocols use geometric shapes or data structure to create a dissemination map.

In the cluster-based approach, mobile hosts form clusters, and these clusters can be used for broadcasting. Inside one cluster, each host is considered as a member. There is one main cluster and one gateway node responsible for relaying messages [55] [68] [69]. Implementation of this structure is costly especially if mobility of nodes is high. Moreover, each node periodically sends 'Hello' messages to declare its neighborhood. The scenario can create a contention and consequently messages will be dropped. In [55], a cluster-based scheme was compared to other schemes and results show that it saves rebroadcasts and has short average broadcast latencies but it leads to a weak reachability in sparse areas.

Unstructured protocols use neighbor nodes knowledge to make broadcast decision. For example, in self-pruning protocol [70], each node maintains the knowledge of its neighbors by periodically exchanging the “Hello” messages. The receiving node first compares its neighbors list to that of sender’s list, and rebroadcast the message only if the receiving set can cover additional nodes. The neighbor knowledge attached with the identity of the node from which the message is received allows a receiving node to decide if it would reach additional nodes by or not re-broadcasting it. Another approach, called scalable broadcasting [71], further enhances the self-pruning scheme by gathering neighbors’ information up to two-hop distance. Thus, each node has two hops topology information. It is worth noting that neighbor knowledge based algorithms also consume extra resources since they require substantial communication between the nodes to exchange the topological structure of the network.

### **3.2 Efficient flooding algorithm**

In this work, we have adapted counter-based scheme in context of nanonetworks. In the scheme, no information about neighbors is required to be maintained by the nodes and rebroadcast decision is based only on local information. This scheme is based on threshold to help nodes to decide whether to rebroadcast or discard received messages. However, in dynamic networks, it is difficult even impossible to determine a priori these parameters. For rebroadcast decision need number of received same messages.

In [43], authors suggest a selective flooding routing mechanism. In this mechanism, a table storing in memory packet ID and source ID associated to latest received messages is used to avoid forwarding the same packet and then prevent an excessive waste of bandwidth. As default, each nanodevice stores information about at most 20 received

packets. In addition, authors conceived a further mechanism for reducing the amount of messages sent into the network: with reference to the hierarchical architecture of a nanonetwork (i.e., nanonode, nanorouter and nanointerface). They imposed that each node must not forward messages in the opposite direction of the destination. Authors propose a broadcasting mechanism in which the message broadcasted immediately by intermediate node if seen for the first time.

Since we are investigating broadcasting by flooding in EM-based nanonetworks, redundant broadcasts will be observed, i.e. nanonodes might receive same packet several times. Excess rebroadcasts are the cause of high-energy consumption and packet collisions. In [55] authors propose counter-based scheme to control broadcasting that decrease number of TX and RX and consequently, energy consumption will be low. In this scheme, when a node receive a message for the first time, it does not rebroadcast the message immediately, but it waits for short time slot before rebroadcasting. While this time interval, the node could hear same packet several times. When the time slot ends, the node checks the number of receptions of the message. If the number is high the node does not broadcast the packet, otherwise it will be rebroadcasted. Average packet delivery time (latency) might be higher than flooding, this is due to delaying, during a fixed time slot, messages in nodes. Threshold for the scheme should be chosen in consideration of network performance.

We have adapted counter-based scheme for nanonetwork. Before describing the scheme, we denote some parameters:  $C$  – threshold, this parameter will be used for rebroadcast decision.  $c$  – counter for packets, each nanonode has its own counter for each message.  $ts$  – short time interval (in femtoseconds) that will be initialized randomly between 0.001 to 10 femtoseconds. The data structure, named *ID-table*, for storing packet



information includes unique ID of a packet, counter for the packet, and boolean variable. In our simulations, we have organized the data structure as a C++ list. Each node has such as list, and during simulation, the list will be filled according to nanonetwork behavior. The counter-based scheme is adapted and is described step by step as follows:

- S1. Initialize counter  $c = 0$  when a message broadcasted for the first time.
- S2. Packet is heard for the first time:
  - S2.1 initialize counter  $c = 1$ ;
  - S2.2 initialize random time slot ( $ts$ );
  - S2.3 schedule rebroadcasting the packet on ( $ts$ ).
- S3. The packet is heard again
  - S3.1 if  $c = 0$ , discard the packet
  - S3.2 otherwise increase  $c$ ;
- S4. Scheduled time of the rebroadcasting the packet is up:
  - S4.1 if  $c < C$  broadcast the message, otherwise cancel rebroadcasting the packet
  - S4.2 fill the *ID-table* with the ID of the packet
  - S4.3 Procedure exits.
- S5. If exactly the packet heard again after it's rebroadcasting by same sender discard the packet.

### 3.3 Performance evaluation

In this section, parameters and metrics considered together with obtained results are presented.

#### 3.3.1 Simulation parameters and metrics

Packet delivery ratio, average latency and number of TX and RX are computed according to network density. Packet delivery ratio (PDR) is the ratio of actual packet delivered to total packets sent. The average latency is the time required for packets to get from source nodes to the destination node. We also computed the number of transmitted (TX) and received (RX) packets, because this number has a higher influence on energy consumption. By using efficient flooding algorithm, we have reduced number of TX and RX by 20% in average compared to simple flooding.

We have chosen 1s as simulation duration by varying the number of nodes from 100 to 500. Physical layer parameters, such as pulse energy, pulse duration and pulse inter-arrival time have been chosen in accordance with [43] [4].

Table 3.2 illustrates scenarios we have considered in the performance evaluation.

| Scenarios | Fixed  | Varied   |
|-----------|--|--|
| 1         | Threshold = 5;<br>Transmission range = 0.01;<br>Packet interval = 0.5 s; | Network density from 100 to 500 nodes with step 100    |
| 2         | Threshold = 5;<br>Number of nodes = 200;<br>Packet interval = 0.5;       | Transmission range from 0.002 to 0.01, with step 0.002 |

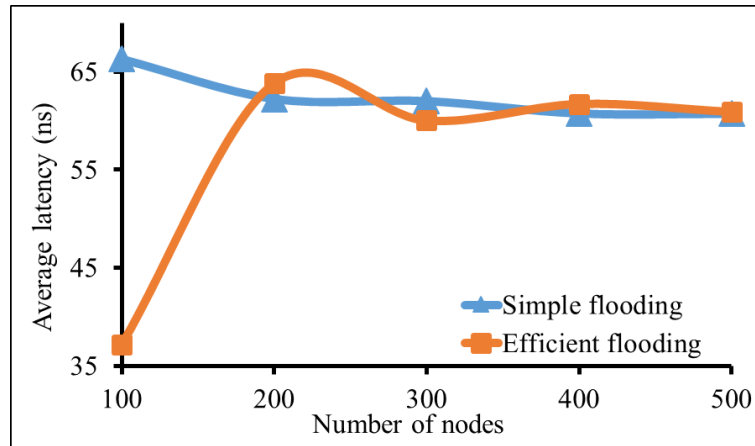
|   |  |  |
|---|--|--|
| 3 | Threshold = 5;<br>Number of nodes = 200;<br>Transmission range = 0.01;         | Packet interval with followings values 0.02, 0.04, 0.1, 0.2, 0.3 |
| 4 | Number of nodes = 200;<br>Transmission range = 0.01;<br>Packet interval = 0.5; | Threshold with following values [1, 9]                           |

**Table 3. 1 Variation of network parameters for evaluation of efficient flooding mechanism**

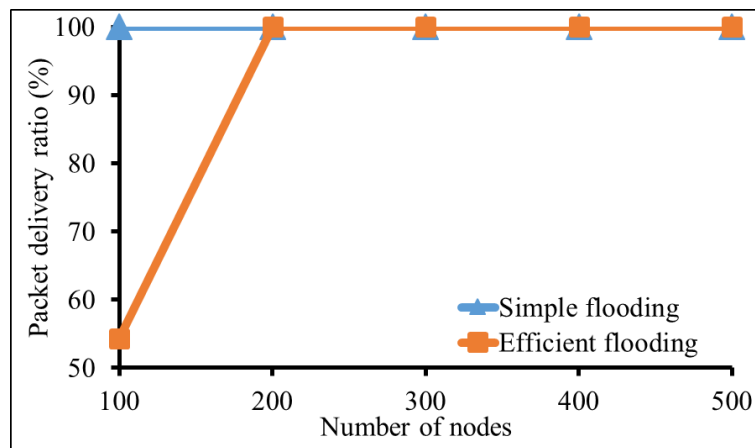
The main goal of conducting these simulations by varying different network parameters is the performance evaluation of proposed efficient flooding algorithm. In other words, we investigate behavior of WSNs in context of average latency, PDR and number of TX and RX by applying simple and efficient flooding algorithms. Comparison results are presented and discussed in figures below.

### **3.3.2 Simulation results**

Figures 3.3, 3.4, and 3.5 present WSNs behavior in context of average latency, PDR, and number of TX and RX in different network densities. Fig. 3.3 depicts changing average latency in varying network density, horizontal and vertical lines present number of nodes and average latency accordingly. This figure compares two flooding mechanisms: simple and efficient flooding algorithms. The results show that in using both algorithms, average latency might be close in case of dense network. In case of sparse network, if we use efficient flooding algorithm, due to disconnected nodes and limitation of rebroadcasting, many packets does not delivered to the destination. Therefore, average latency gets lower value (in our simulations average latency gets about 37 nanoseconds (ns)). In dense networks, average latency get values in 60-67 ns.

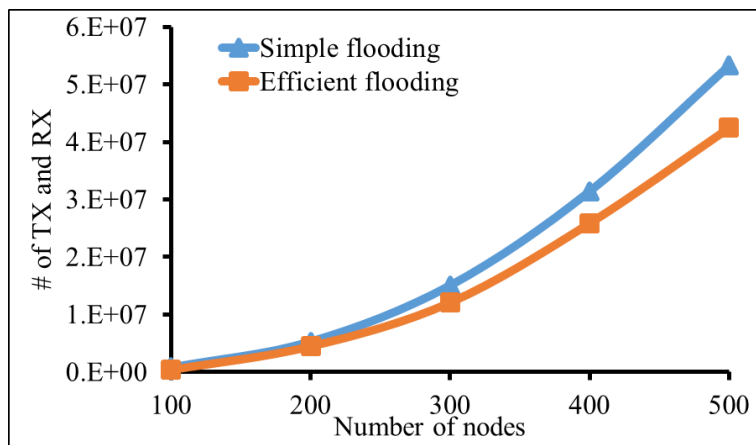


**Figure 3.3 Impact of density: average latency**



**Figure 3.4 Impact of density: PDR**

The same situation is observed for PDR (Fig. 3.4), it can be seen that PDR is small in sparse network when using efficient flooding algorithm. This behavior arise due to disconnected nanonodes and limitation of rebroadcasting by using threshold values. In dense networks, it can be observed that PDR reached 100% throughput. In fact, with consideration of network mobility, the situation could arise in dense network also. Due to mobility, some parts of a network could be scarce. In usage of simple flooding packets flow freely in network and reach to gateway. It should be mentioned that gateway node discards a packet, if it has been received before via other flow.

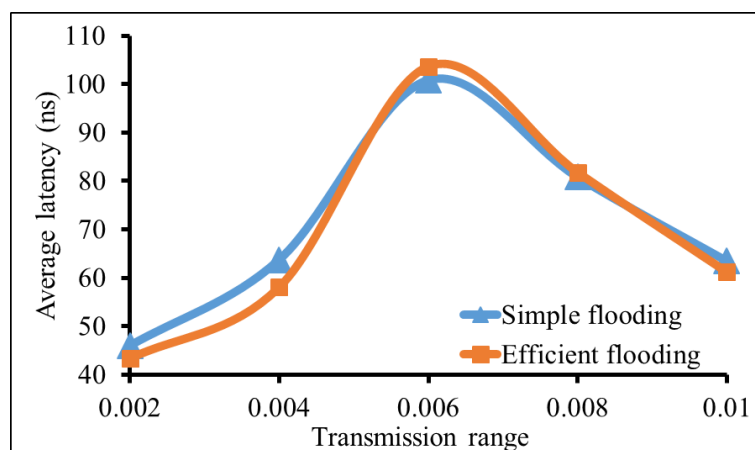


**Figure 3. 5 Impact of density: number of TX and RX**

Fig. 3.5 presents number of TX and RX of all nodes during simulation time. In fact, high number of TX and RX is a cause of energy hunger of a network. Especially, transmission process requires more energy compared to reception process, it will be reminded in chapter 4 also. In case of using efficient flooding algorithm, we expect that total number of TX and RX gets much lower compared to simple flooding algorithm. Indeed, Fig. 3.5 proves that total number of TX and RX get much lower values in different network densities compared to simple flooding. In our simulations, we have observed that especially transmissions much reduced due to limitation of rebroadcasts. In the simulations of WSNs, we have chosen threshold value as 5, we have supposed that this is the most compatible value for different network densities. It means that if a nanonode receive same message more than five times before rebroadcasting, the message will be discarded. The figure shows that in usage of simple flooding algorithm this number gets higher value. Thus, using efficient flooding algorithm does not have serious consequences while designing dense network, it helps reducing redundant rebroadcasts and save energy.

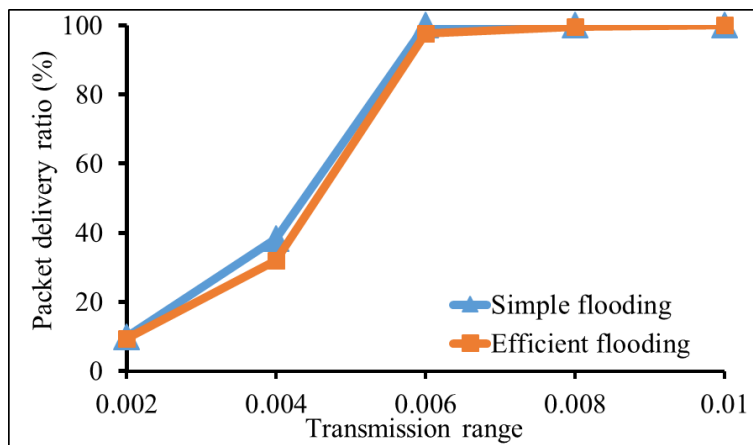
We have investigated WSNs by fixing number of nanonodes, threshold, and packet interval and *varied transmission range*. Figures 3.6, 3.7, and 3.8 indicates three basic

parameters of efficiency of a network. Fig. 3.6 shows that using both flooding algorithms does not affect the average latency. In case of lower transmission range due to disconnected nanonodes few packets are delivered and consequently, we have observed lower average latency. Indeed, it can be seen that when the transmission range fixed as 0.002, in both cases of using flooding algorithms, average latency gets low. With increasing transmission range, average latency gets higher value. Actually, we expect high packet delivery ration with lower latency. We can say that when transmission range fixed as 0.006 m, is the worst case for latency. It is due to high number of hops are needed to deliver packets between source nodes and destination node, accordingly, higher average latency is observed. When we fix the transmission range as 0.01 that is high value for the network density and boundaries, the average delay gets lower due to low number of hops that packets cross to reach the destination node. However, in this case might be observed huge number of collisions.



**Figure 3. 6 Impact of transmission range: average latency**

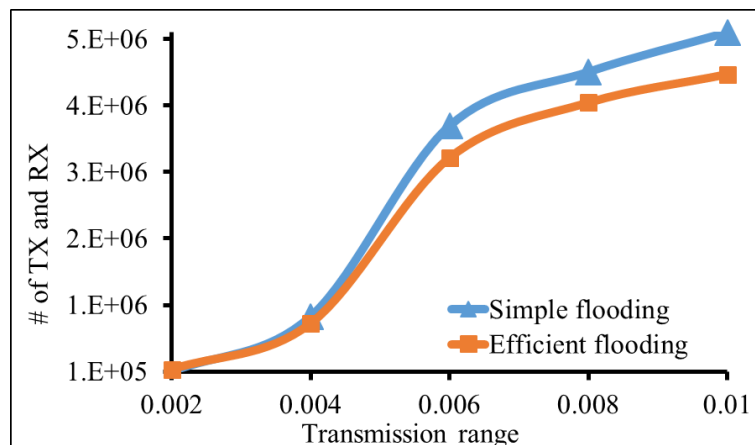
Thus, it shows that configuring most compatible transmission range value with consideration of low average latency and network density is an important issue that should be resolved.



**Figure 3. 7 Impact of transmission range: PDR**

Fig. 3.7 depicts the packet delivery ratio, and shows that in both cases the PDR is almost same. When we have fixed transmission range as 0.002, worst PDR is observed. This is due to disconnected nodes, in other words, because of short transmission range nodes cannot find any neighbor around and discard received packets. It could be seen that few packets are delivered when the transmission range is low. In this case also by increasing transmission range PDR increases accordingly. It is explained with increasing neighbors of nodes. When transmission range reaches  $0.006\text{ m}$ , the PDR gets almost  $100\%$  in both case of using flooding algorithms. However, fixing the transmission range  $0.006\text{ m}$  makes packets flow through network with high latency, and we do not recommend the value as a transmission range. If we fix it 0.008 and 0.001 that is high value of transmission range, we observe  $100\%$  PDR. Obviously, these is a good result for both PDR and average latency. However, with increasing number of nodes, because of collisions PDR might be lower. We have provided simulation of WNSN with 200 nodes.

Thus, finding transmission range value that increase PDR and decrease average latency is a difficult task. Moreover, transmission range value should be chosen so, that TXs and RXs should get lower values. This issue has been investigated in following figure.



**Figure 3. 8 Impact of transmission range: number of TX and RX**

Fig. 3.8 shows the number of TX and RX. Same situation have been observed, by using both flooding algorithms. In case of using efficient flooding algorithm, we have reduced number of TX and RX by 20% in average compared to simple flooding, especially when the transmission range is above 0.006. Importance of reducing TX and RX have been proved in other sections.

Thus, in conclusion we can say that 0.008 value is more compatible for the WNSNs that we have simulated. Because, by fixing this value as transmission range, we have observed relatively lower average latency, higher PDR and smaller number of TX and RX especially when we have used efficient flooding algorithm.

Simulations are also conducted to study the influence of data traffic. We have fixed number of nodes (200), threshold value (5) and transmission range (0.01) and varied the packet interval. By reducing time interval between packet generations, we have loaded the network. In other words, in these scenarios, generating packets will be changed for every simulation. For example, if packet interval is 0.02 s, we assume that WNSN is overloaded. Figures 3.9 and 3.10 show that changing packet interval does not affect average latency and PDR. As observed in other simulations presented above, in usage of



efficient flooding algorithm gives better results compared to simple flooding as presented in Figure 3.11.

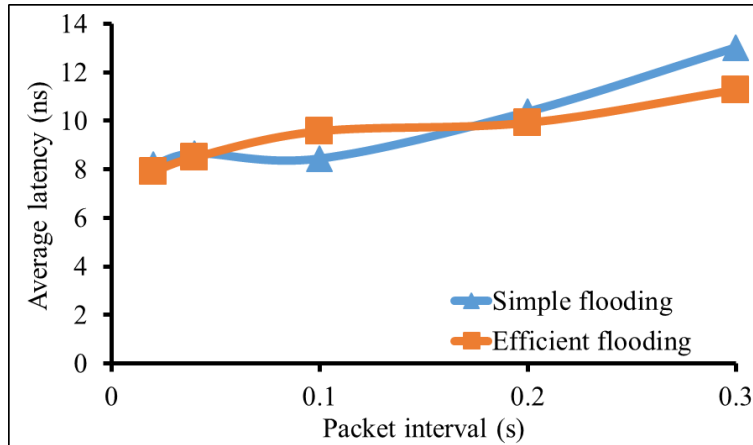


Figure 3. 9 Impact of packet injection rate: average latency

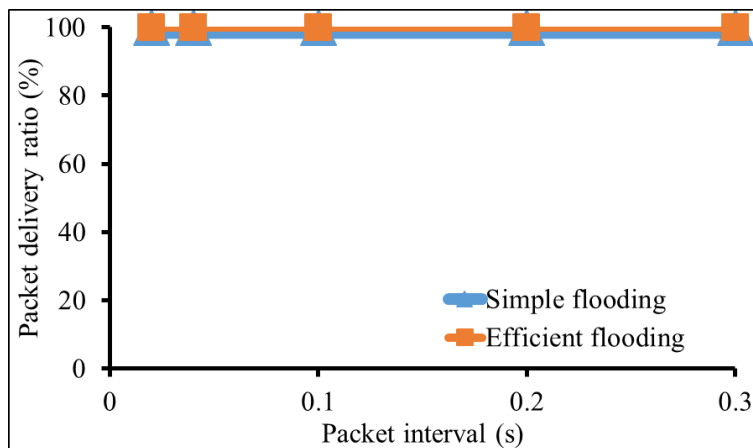


Figure 3. 10 Impact of packet injection rate: PDR

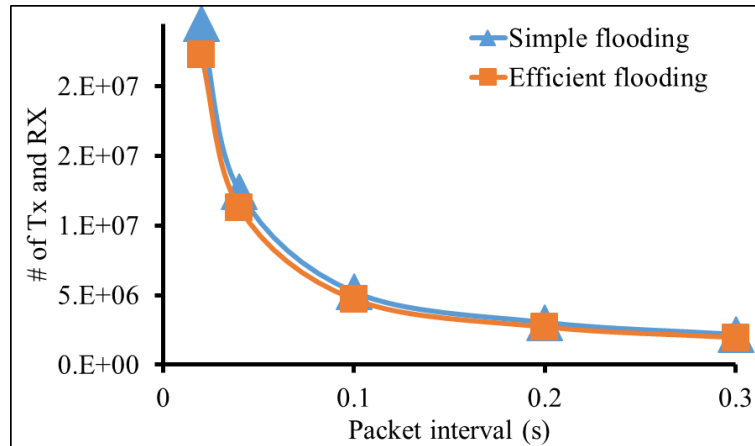


Figure 3. 11 Impact of packet injection rate: number of TX and RX

Simulations have been also conducted to investigate network behavior in case of varying threshold values. Theoretically, it is expected that by decreasing the threshold value, number of rebroadcasting should reduce. Also, decreasing threshold is the cause of low PDR. Therefore, threshold should be tuned in consideration of network density and transmission range of nanonodes. Simple and efficient flooding algorithms are compared in figures below, simulations are conducted by fixing number of nodes (200), transmission range (0.01) and packet interval (0.3). Threshold varied from 1 to 9.

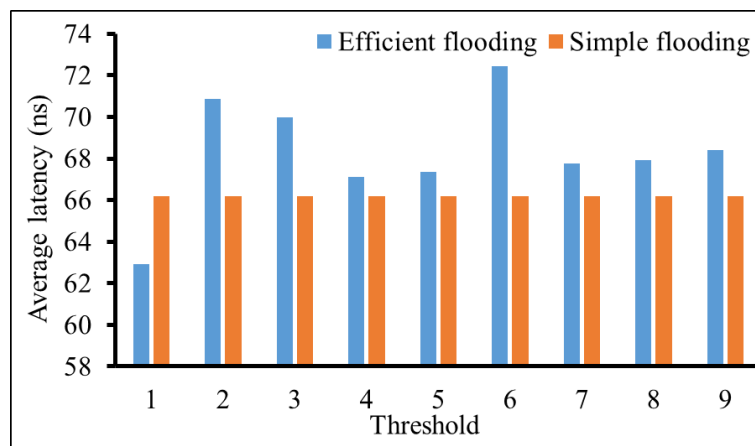
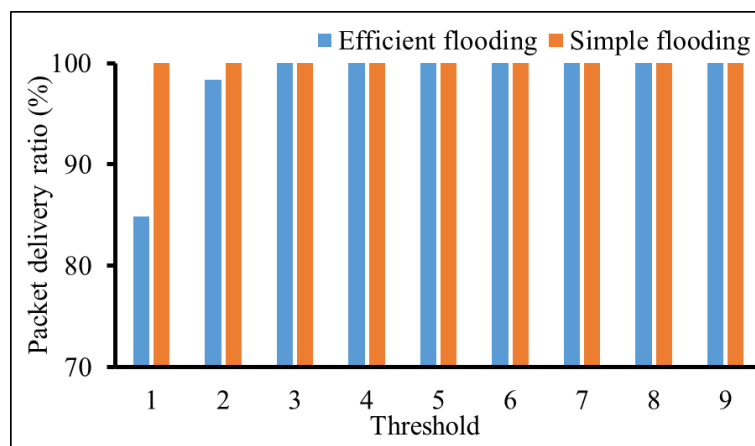


Figure 3. 12 Impact of threshold: average latency

Figure 3.12 shows that the average latency gets different values for different threshold values. By the rules of efficient flooding algorithm, every packet rebroadcasts after short time that initialized randomly and average scheduled time could be different for each simulation of WNSNs. In other words, packets could delay longer in some nodes. Therefore, these differences observed in the results.

Figure 3.13 shows that low value of threshold is the cause of low packet delivery ratio. In these simulations each WNSN consists of 200 nodes and it is a sparse network considering network boundaries. PDR gets higher values for dense networks. Due to limitations of transmissions and receptions by using counter parameter, when counter value is small, PDR also get lower values. When we have fixed counter to 3, it can be seen in the figure that PDR reaches values same with simple flooding. However, it does not mean that we have not limited number of TX and RX.



**Figure 3. 13 Impact of threshold: PDR**

Low threshold value gives better results for number of TX and RX (fig. 3.14). By increasing threshold, number of TX and RX approaches to flooding. We observed when threshold is 7 or high, this number will be same as simple flooding. Results show that tuning threshold with 3, gives better results for every performance evaluation metrics of

nanonetwork. When threshold is 3, PDR is *100%*, number of receptions and transmissions is low, better results are expected for average latency and PDR.

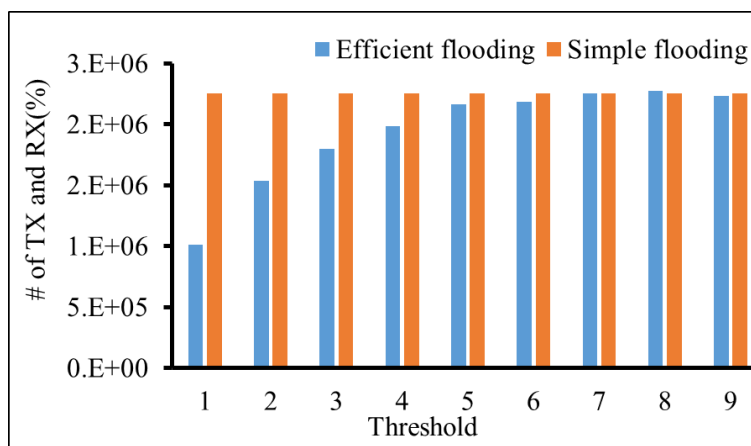


Figure 3. 14 Impact of threshold: number of TX and RX

### 3.4 Conclusions

In this chapter, we have presented an efficient flooding algorithm in WSNs. Briefly, the principle of this scheme is as follows: if during the scheduled time of rebroadcasting a packet, the number of received same packets is small, rebroadcasting will be performed. Counter value might help nodes figure out the network density. If counter is high, network or its part that node is located might be dense. Sparse network also suffers from high threshold, since nanonodes could receive same packets rarely. Choosing high threshold affects overall evaluations of dense network; in this case, efficient flooding algorithm might not be effective in reducing redundant rebroadcasts. The effectiveness of the proposed algorithm has been proved by simulations. The results show that the algorithm gives better results than flooding, especially in context of excessive broadcasts. The efficient flooding algorithm reduce packet collisions and number of RX and TX, which influence directly on energy consumption.

## Chapter 4: Adaptive transmission range approach

In this chapter, an adaptive transmission range of electromagnetic-based communication mechanism is introduced. Simulations are conducted with fixed and adaptive transmission ranges to show the efficiency of the proposed approach in terms of throughput and latency according to the network density.

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## 4.1 Introduction

A WNSN is formed of tiny nanonodes with limited sensing, computation, storage and power capabilities. In forming well connected WNSN, coverage area or transmission range of nanonodes should be carefully tuned according to the network density. The aim is to minimize contentions while maintaining good latency, high throughput and minimize energy consumption under different network densities. For example, a larger transmission range will increase the number of neighbors and contribute higher progress, if only the transmission is successful, it guarantees low latency with high PDR. However, increasing transmission range too much might increase the probability of collisions. Due to short transmission range, nodes disconnect from each other, consequently, a few packets will be delivered with high latency, since the number of hops to deliver messages will be high.

Taking into account the above-mentioned issues associated with the transmission range, some approaches are required to allow adapting the transmission range of nanonodes based on network density. However, selecting dynamically and in a distributed manner the best suitable range for each node is a difficult issue. In the rest of this chapter, we first present short overview of transmission range control, and then we describe our proposal related with adaptation of transmission range control for WNSNs in different network densities. The results of simulations obtained in our first investigation of the EM-based broadcasting mechanism for nanocommunication.

## 4.2 Transmission range control

When source and destination nodes are located far from each other, message delivery requires multi-hop scenario. On the one hand, high transmission range decreases packet

delivery time, unfortunately, in this case, redundant rebroadcasts and collisions will be observed, and this scenario requires high-energy consumption. The requirement drastically increases in dense networks. Consequently, nodes could be disconnected from network very fast and the whole network might stop functioning. On the other hand, using low transmission range might decrease requirement to energy consumption for one-hop transfer. However, if message delivery requires large number of hops, this scenario also might require high energy consumption. Furthermore, in this case, an issue arises related with delivering messages due to disconnected nodes. Therefore, tuning techniques for acceptable value of transmission range becomes very important mainly in mobile ad hoc networks.

As a solution such a problem, critical transmission range (CRT) approach is presented in the literatures [72]. Let us consider that all nodes have same transmission range  $r$ . The major issue is to find the minimum value of  $r$  (the CRT), and setting  $r$  as a transmission range of all nodes of a network should not affect to major metrics (such as throughput, packet delivery ratio, energy consumption). In [73], optimal transmission range for wireless ad hoc networks based on energy efficiency is investigated. Researchers determined the optimum transmission range. Uniformly distributed networks spend less energy using this transmission range. They assume the existence of forwarding neighbors and the knowledge of their locations, first derive the average per-hop packet progress for a transmission range that is universal for all nodes, and then use the result to determine the optimal per-hop transmission range that gives the maximal energy efficiency. The relationship between the most energy-economical per-hop transmission range and the node density, as well as the path-loss exponent, is then numerically investigated. It was observed that the optimal transmission range varies markedly in accordance with the node

densities at low path-loss exponent values (such as two) but remains nearly constant at high path-loss exponent values (such as four).

### **4.3 Adaptive transmission range approach**

In forming well connected nanonetwork, the transmission range of nanonodes should be carefully tuned according to the network density. For example, a larger transmission range will increase the number of neighbors, which could guarantee low latency with high packet delivery ratio. In other words, increasing too high the transmission range might increase the probability of packets collision, and shortening it too much might disconnect nodes from each other. In this case, small number of packets will be delivered with high latency, since the number of hops among nanonodes will be high.

We have considered that nanonodes are replaced in cuboid and they move according to the Gauss-Markov mobility model. In our first evaluation of nanonetworks, several issues have been noticed. For example, when a node should send or re-broadcast a packet it checks first for its neighbors using information from the channel layer. If there are no neighbor nodes in its coverage area, packets will be destroyed. There is a possibility that the packet could be got/returned back to the transmitter from other neighbor nodes after several hops or directly after transmission. In this case, packets will be also destroyed. In order to avoid this issue, we should consider the following cases: (i) in sparse nanonetwork, the probability of finding neighbors is very low. In this case the transmission range of nanonodes needs to be adapted to keep network connectivity; (ii) in dense nanonetwork, throughput could be low because of collisions. In this case the transmission range needs to be adapted to minimize the collisions.



It is worth noting that when we assign short/long transmission range in dense/sparse network, results for throughput and average latency are better compared to a fixed transmission range. For adapting the node's transmission range the two cases described above have been considered. In the first case, when an intermediate transmitter has no neighbors, we assign higher transmission range in the channel layer, which might increase the number of neighbors. In the second case, the transmission range takes the value of the average value of distances to all its neighbors.

## **4.4 Performance evaluation**

In the evaluation of EM-based broadcasting mechanism, we considered that nanonodes are replaced in finite environment and they move inside it according to the Gauss-Markov mobility model. In this work, we have used the flooding algorithm that already implemented in Nano-Sim. In this algorithm, packets travel in the nanonetwork hop by hop, until it reaches the gateway node. Nanonodes generate packets according to fixed time interval and broadcast them to neighbors. Each packet is identified with a unique packet ID and a source node ID.

### ***4.4.1 Simulation parameters and metrics***

Simulations have been conducted using several parameters as follows. We varied network density rising from 100 to 500 nanonodes in the finite environment. The bounds of the environment are the same for each network. The position of each nanonode changes during simulation time in accordance with the mobility model. Nanonodes periodically broadcast generated packets in fixed time to neighboring nodes. Thus, packets are rebroadcast from one to others until they reach the gateway. The gateway node is an

interface between the nanonetwork and external network, e.g., Internet. Other simulation parameters are presented in Table 1.

| <b>Parameter</b>              | <b>Value</b>                            |
|-------------------------------|---|
| Number of nanonodes           | from 100 to 500                         |
| Area                          | $10^{-3} \times 10^{-3} \times 10^{-2}$ |
| Pulse energy (pJ)             | 100                                     |
| Pulse duration (fs)           | 100                                     |
| Pulse Inter arrival Time (ps) | 10                                      |
| Transmission Range (cm)       | from 0.001 to 0.01                      |

**Table 4. 1 Simulation parameters for evaluation adaptive transmission range**

We investigated the impact of fixed and adapted transmission range and two main performance metrics are computed, the throughput and average latency. The throughput represents the percentage of packets that are delivered. The average latency represents the time needed for packets to arrive at their destination.

#### **4.4.2 Simulation results**

First, we simulated WNSN by varying network density and for each network we varied the transmission range of nanonodes to observe network behavior. During each simulation the value of transmission range does not change.

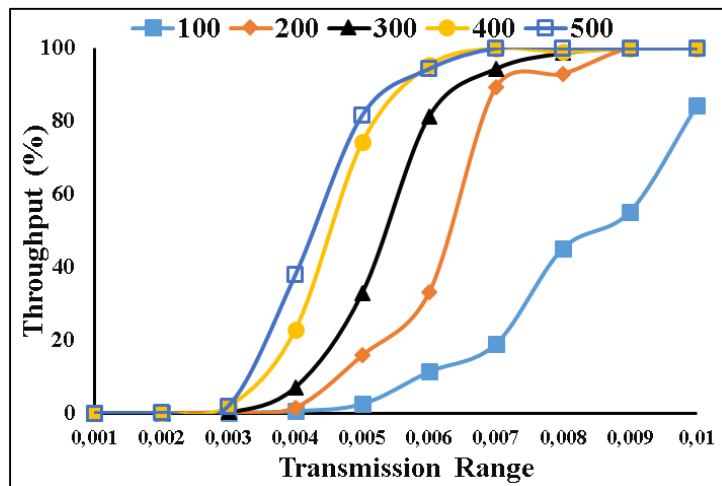


Figure 4. 1 Throughput vs Transmission range

Figure 4.1 reports the throughput according to the fixed transmission ranges of nanonodes. It can be noticed that the throughput is low for sparse networks and high for dense networks. For example, in high dense networks (i.e., more than 400 nanonodes) the throughput reaches 100% with a transmission range higher than 0.006. For medium dense networks (i.e., 200 to 300 nanonodes), 100% throughput is reached when the transmission range is higher than 0.008. However, for sparse networks (less than 100 nanonodes) the throughput reaches only about 80% with the transmission range fixed to 0.01. In other words, the throughput increases from low to high dense networks; it reaches 100% for highly dense networks. This is mainly due to the effects of nodes density on the packets losses, i.e., for a high density, the network is more connected and almost all packets will reach the destination node.

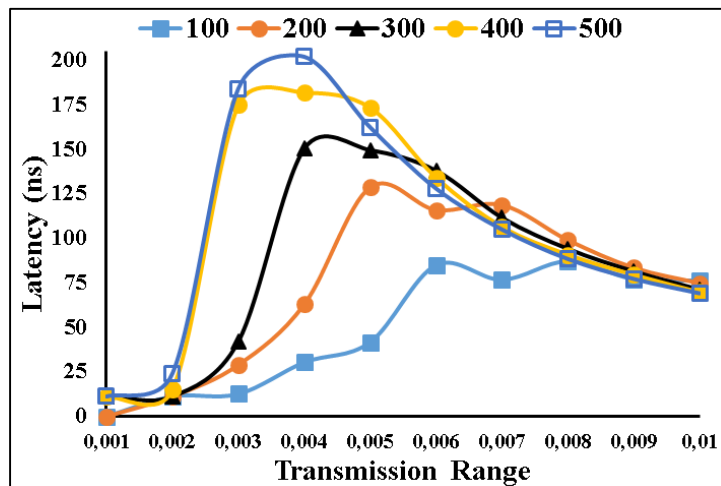


Figure 4. 2 Latency vs Transmission range

Figure 4.2 shows the impact of network density on the broadcast speed by computing the average latency. These results verify the strong correlation between the broadcast speed and the network density. More precisely, the average latency is higher for dense networks compared to sparse networks for all fixed transmission ranges. Average latency is very high (i.e., more than 150 ns) for high dense networks (i.e., 400 and 500 nanonodes) when the transmission range is fixed between 0.003 and 0.005. This is due to the high number of hops needed to reach destination. Average latency for medium dense networks (i.e., 200 and 300 nanonodes) also increased in the same transmission range interval, but less than 150 ns. When the transmission range is initialized higher than 0.008, average latency is almost same for all number of nodes. It is due to the same number of hops needed to deliver packets from nodes sources to the destination node.

From these results, due to short transmission range, multiple hops are needed to send packets to any other nanonodes in the network. Thus, as the transmission range increases a few hops are needed for packets to reach the gateway. The packets will only be broadcasted few hops away, which influence on latency and throughput. However, we can see also that the transmission range is linked to network density. For example, in high

dense network (e.g., 500 nanonodes), increasing the transmission range allows quickly the network to sustain 100% throughput while maintaining low latency. In low dense network, even with high transmission range, the network could sustain around 60% throughput. These results confirm the hypothesis stating that different transmission range values need to be assigned based on network density. Therefore, we proposed an adaptive approach for tuning the transmission range of nanonodes based on network density.

After this first investigation, we studied the adaptation of transmission range according to the network density. In other words, transmission range of each nanonode changes with respect to the number of its neighbors during simulation time. The main objective is to keep connectivity among nodes, increase overall packet delivery ratio in sparse network, and reduce redundant transmissions and minimize packet collision in dense network.

When a nanonode should send or rebroadcast a packet, it checks first for its neighbors. To get information about neighbors, every nanonode uses the channel layer. In case of fixed transmission range, when a nanonode does not find any neighbor inside its coverage area, packets will be destroyed. In order to avoid this issue, the following cases should be considered: (i) the probability of finding neighbors is very low in a sparse network. In this case, the transmission range of nanonodes should be adapted to keep network connectivity; (ii) throughput could be low because of collisions in dense nanonetwork. In this case, the transmission range also should be adapted to minimize the packet collisions.

It is worth noting that when we assign short/long transmission range in dense/sparse network, performance results are better than fixed transmission range case. For adapting the node's transmission range, in the first case, when an intermediate transmitter has no neighbors, we assign higher transmission range in the channel layer, which might increase the number of neighbors. In the second case, the transmission range takes the value of the

average value of distances to all its neighbors. Obtained results are presented in the following figures.

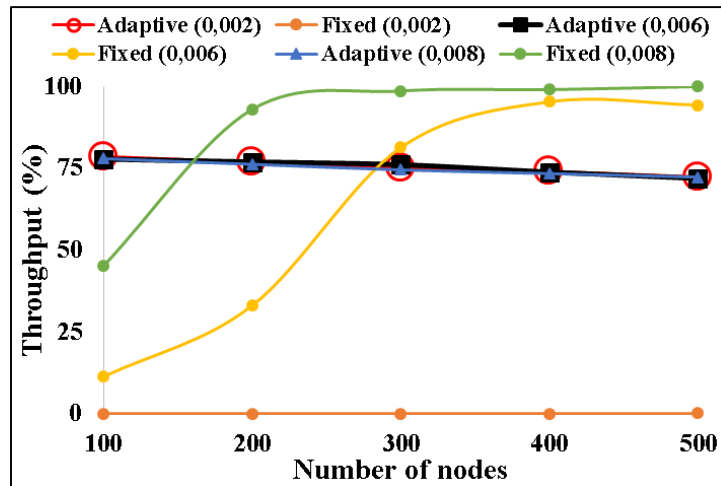


Figure 4. 3 Throughput vs number of nanonodes

Figure 4.3 shows the impact of network density on throughput using two strategies: fixed and adaptive. In the beginning of simulations, initial values of transmission ranges are same (equal) for both strategies. For the fixed strategy, the transmission range does not change during the simulation, while in the adaptive strategy the initial value changes as simulation time elapses. Simulations are conducted with different initial transmission ranges (0.002, 0.006 and 0.008). The network density is varied from 100 to 500 in same area by changing it from sparse to dense networks. Simulations show that when we use fixed transmission range, depending on network density, results for throughput might be different. When we assign a low value for transmission range and fix it, in sparse network, throughput is low, because the probability of finding neighbors in this transmission range is very low. While in dense and medium network, results of throughput gets better. When we use the adaptive strategy, results are more stable for any network density. In this case, throughput gets about 75%.

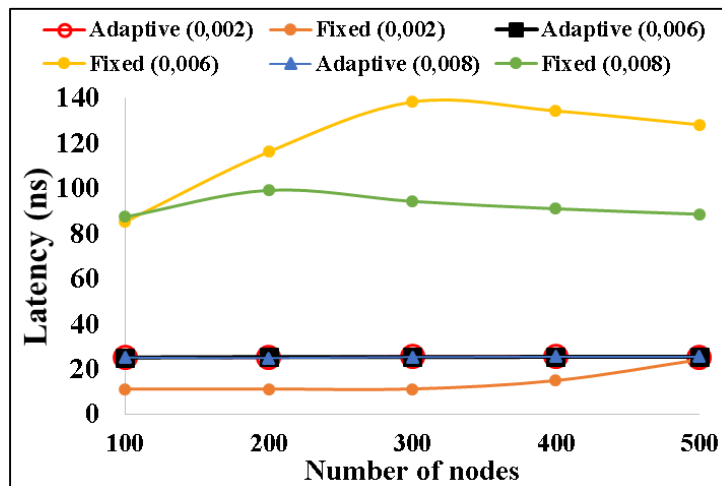


Figure 4. 4 Latency vs number of nanonodes

Figure 4.4 represents the comparison of average latency when we adapt and fix transmission ranges with dense, medium and sparse networks. Simulation results confirm that the adaptive transmission range strategy outperforms the fixed transmission range strategy in terms of average latency. When the transmission range is fixed with initial value 0.002 the average latency is very low due to low throughput (Figure 4.3). By using adaptation rules of transmission range both metrics get much better results. In case of fixing transmission range with initial value 0.006, we observe a high latency compared to other values. It is due to the high number of hops needed to deliver packets from a source to destination node. When we initialized the transmission range with 0.008, and do not change the transmission range value, it can be seen that latency is lower and throughput is higher. However, using adaptive transmission range the average latency gets smaller for all WSNs. It could be observed that since we use adaptive transmission range the average latency is small (between 20 and 30 nanoseconds).

In summary, we can conclude that adapting transmission range of nanonodes provides good results in terms of throughput and latency. In case of using adapting rules in sparse network the transmission range increases and average latency and throughput improves.

## 4.4 Conclusions

In this chapter, we have first investigated impact of transmission range on the performance of the EM-based broadcasting mechanism for nanocommunication. The results obtained from the first investigation showed that in order to limit packet flooding while increasing throughput and decreasing latency according to a given network density, node's transmission range needs to be tuned. For example, when we fixed the transmission range of nanonodes the throughput was very low in sparse networks. For example, with 100 nanonodes it reached only about 80% with maximum tested transmission range, 0.01 cm. In dense (500 nanonodes) network 100% of packets are delivered with 0.004 as a transmission range value. It was also noticed that latency decreases with increasing transmission range. We then introduced an adaptive transmission range approach that allows nodes to select the best suitable transmission range in order to increase network connectivity. Result showed that this approach provides a good throughput while minimizing latency.



## Chapter 5: Nano-NoC for SoC design

In this chapter, the performances of EM-based nanocommunication mechanism as an on-chip interconnect for System on Chips (SoCs) are evaluated. The aim of the investigation is to analyze the behavior of communication in Nanoscale Network on Chip (Nano-NoC). Firstly, we briefly introduce function of NoC and its mechanisms and aspects. In this section, we present the characteristics of NoC architectures that are adapted from other computer networks. Secondly, we introduce RFI-wireless and photonic NoCs, and their advantages. Thirdly, we present existing NoCs communication mechanisms. Finally, we present results of simulations of Nano-NoC. Two routing techniques, flooding and XY routing, are evaluated using four traffic patterns, such as Bit-Reversal, Shuffle, Transpose and Uniform. A 2D Mesh-like nano-OCI architecture is considered. Several performances metrics, such as the average latency, the throughput and the energy consumption, are computed by varying the number of nanonodes and the transmission range.

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## 5.1 NoC, a quick introduction

Performance evaluation of systems becomes very difficult or impossible in many cases due to the large number of Intellectual Property (IP-) modules in the SoC, when the interconnection architecture of such systems is based on bus topology. In the current state of information technologies, any system requires intensive parallel communication. However, buses might not ensure required bandwidth, latency and energy consumption. Therefore, Network on a Chip (NoC) is proposed as a solution to tackle these issues [74]. NoC is an embedded switching network that provides interconnection among IP modules in SoCs.

Links (or channels), routers and Network Adapter (NA) or network interface (NI) are the main components of NoC. Links physically connect the nodes of SoC by using point-to-point or bus topology. Routers are responsible for implementing communication protocols. Communication protocols are the set of rules of handling various issues arising functioning NoC, such as packet collisions, avoiding deadlock, increasing throughput, decreasing latency, etc. NA is makes the logic communication between IP-modules.

Communication protocols of computer networks have been adapted for NoC. Therefore, most of the features of communication protocols could be used NoC. For example, the Open Systems Interconnection (OSI) model is adapted for NoC. However, not all layers of the OSI model are applied for NoC. Generally, NoC has following layers: application and presentation layers, session and transport layers, network layer, and Link and data layer (figure 5.1) [75].

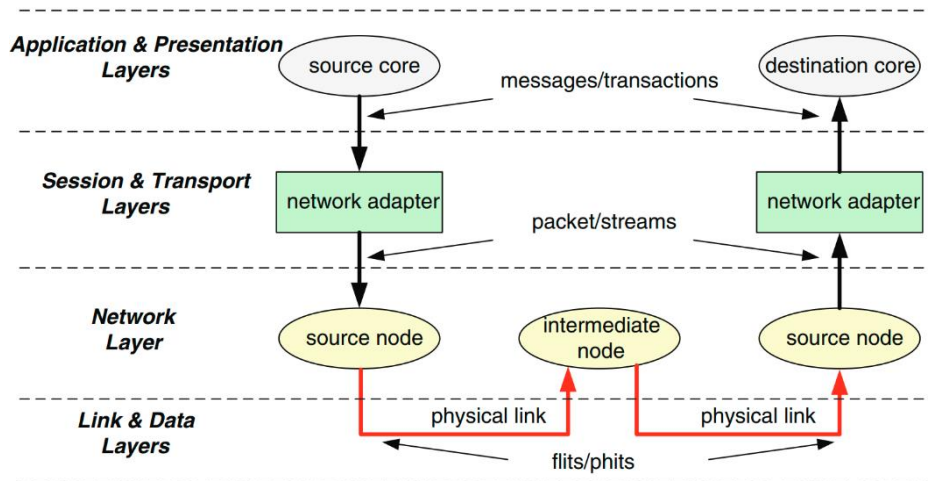


Figure 5. 1 ISO/OSI reference model for NoCs [75]

Several topologies are presented for NoC [75]. The 2D mesh topology is often used for NoC. Every switch that is not located in the edge of the mesh, have four neighboring switches and one router. Also it is supposed that lengths of the links are equal as illustrated in Figure 5.2. Moreover other topologies used in designing NoC: 1-D torus, 2-D torus, Folded torus, Octagon, Fat-tree, Butterfly-fat tree, Polygon, and customized.

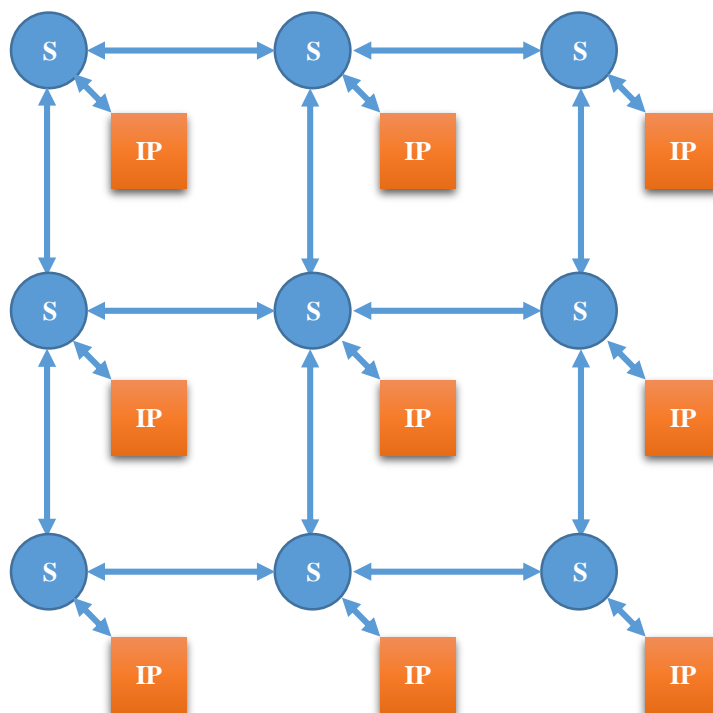


Figure 5. 2 3x3 2D mesh topology for NoC

## 5.2 Wireless NoC

Researches show that due to metallic interconnects used in current SoC design high latency and energy consumption might be noticed for large SoCs. Usual NoC topologies, i.e., mesh and torus with metallic interconnects, do not require high latency and energy consumption in short communication distances. With the increase of this distance, the whole network suffers mentioned issues. [86]. Recently, Radio Frequency (RF)/Wireless NoC, 3D NoC, photonic NoC have been introduced to alleviate these problems by, for example, replacing some of the multi-hop wire links with high-bandwidth single-hop long-range wireless channels [50] [87].

Authors of [86] counted benefits of implementing radio frequency (wireless) interconnection in NoC: (i) high energy efficiency for long, one-hop communication; (ii) reduced complexity compared to systems with waveguides or wires; (iii) compatibility with CMOS wireless technology designs.

In [88] the design of a wireless NoC architecture is demonstrated. This work considers tiled multi-core design. The architecture of wireless based NoC is based on conventional wired 2D mesh NoC architecture called Network-based Processor Array (NePA). Every Processing element (PE) consists of a processor core, Network Interface and a router. Each router has bidirectional links connecting with neighbor router. Figure 5.3 depicts on-chip wireless NoC. Wireless NoC with 10x10 PEs divided into 4 rectangular subnets and Wireless Routers (WRs) are located at the center of each subnet. In designing this kind of wireless NoC, communication between some routers replaced with WR and wireless routers are able to transfer packets through wired and wireless channels. To distinguish the two kinds of routers in wireless NoC, authors named the router in NePA

as Baseline Router (BR). In wireless NoC, PEs are divided into various subnets which have one WR responsible for providing wireless communication for the PEs in the same subnet. WRs allocation in subnets is an important issue to decide system performance. Solid lines and dotted lines represent wired and wireless links, respectively, for transmitting packets between routers. Due to availability of multiple channels, Frequency Division Multiple Access (FDMA) technique is adopted for channelization to achieve simultaneous multiple communications between WRs. Each wireless transmitter and receiver pair uses an independent carrier frequency to accommodate data from different channels.

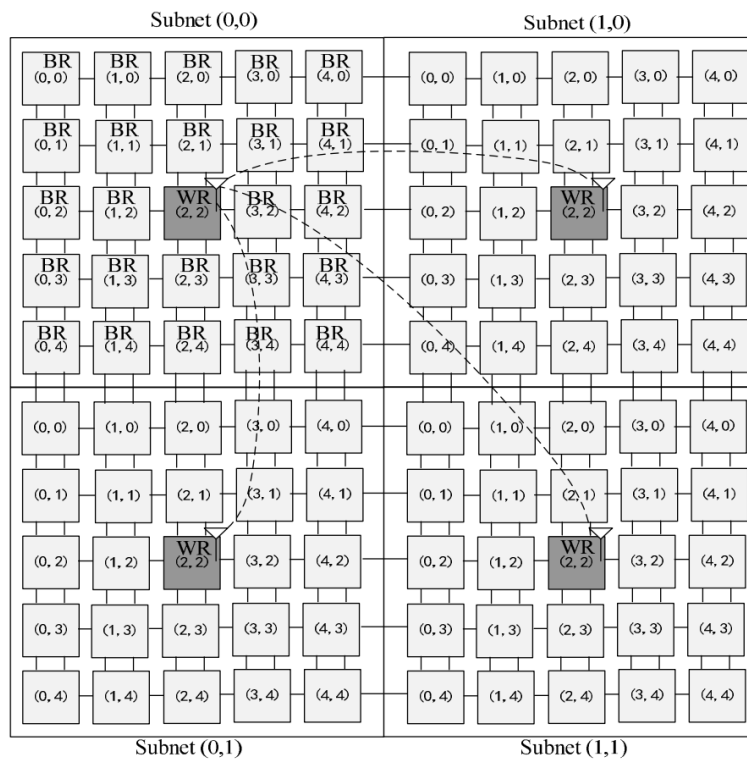


Figure 5. 3 10x10 Wireless NoC architecture [88]

### 5.3 Photonic NoC

The achievement in the field of nanoscale silicon photonics gives improved controlling over optical properties of a device [89]. Photonic interconnection-based networks provide low power dissipation, high throughput and low latency. One of the main objective of implementing photonic NoCs is reducing energy requirement on intra-chip communications. The key power saving rises from the fact that once a photonic path is established, the data are transmitted end to end without the need for repeating, regeneration or buffering. In electronic NoCs, messages are buffered, regenerated and then transmitted by routers. Moreover, they several times route to reach their destination [90].

In [90] the design of optical NoC is presented, performance evaluations are conducted considering main metrics of evaluation any network, such as low latency, energy consumption. Nanoscale photonic integrated circuits (PICs) are the main members of the optical based NoC. Optical microcavities are used in the design of PICs. Microcavities can easily fabricated on conventional silicon and silicon-on-insulator (SOI) substrates. By using PICs can be implemented high interconnection bandwidths. Moreover, less power and less latency will be expected than their modern analogs.

In [90] hybrid NoC architecture that uses both optical and electronic interconnection has been proposed. In the architecture, transmission of packets have been performed through optical interconnection and electronic interconnection have been used for distributed control and short message exchange.

## 5.4 The design of on-chip interconnection via Terahertz band

The latency and the energy consumption of the inter-chip communication are the major obstacles [91]. CMOS integration gave an opportunity to develop millimetric on-chip antennas that radiate in the GHz band and high frequency transceivers. On-chip antennas allow the creation of inter-core wireless links within the Wireless Network-on-Chip paradigm [91]. Nanotechnology offers the possibility of interacting either with the biological or the non-biological nanoscale. This interaction may be through simple but skilled elements like nanoparticles or assembled structures named nano-processing-elements (nanoPEs). NanoPEs are assumed to be mobile and rapidly deployable. Generally, the main function of nanoPE is to sense events in surrounding environment and inform neighbors about the events using mechanical, acoustic, molecular or electromagnetic communication methods. They can be defined as autonomous units composed of nanoscale structures capable of performing simple tasks, such as sensing, local actuation, basic computations or data storing (Figure 5.4) [1].

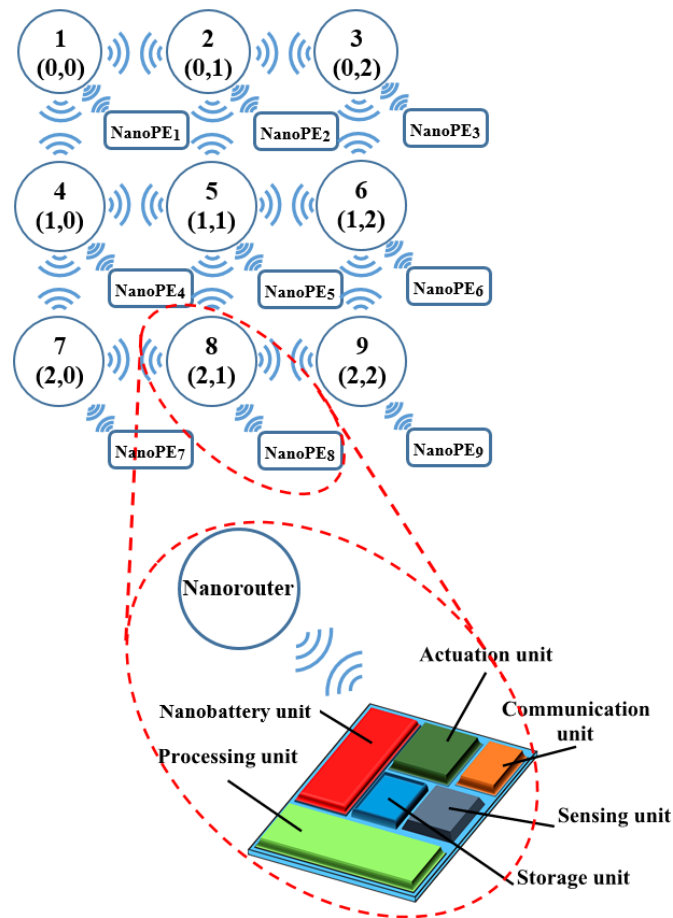


Figure 5. 4 Mesh-like Nano-NoC topology

Nanotechnologies are now in an advance mode that enables to build-up low-cost, low-power and multiple functional tiny nanodevices, such as nanoPEs and nanorouters [92]. Their dimensions depend, amongst other factors, on the subunits that a nanodevice contains. However, since they are supposed to interact with nanoscale entities in a non-invasive way, the nanodevices ranging in size from  $10\mu m^2$  to  $100\mu m^2$  are considered. Like nanodevices in WNSNs, NanoPE should be designed to perform difficult tasks, such as complex computing, saving big data, and sensing huge areas. NanoPE also should be equipped with nanobatteries and it is better if they have ability charging from mechanical, vibration or hydraulic energy. For designing sensing unit of electromagnetic-based (EM-based) nanoPE GNRs and CNTs might be used. However, while technology miniaturized



and become faster and more energy efficient, wires used for communication are performing slowly and more energy hungry. Communication between nanoPEs is still one of the most important issue needs to be addressed [1].

For example, in [1] authors introduce nanosensor technology and EM-based communication among them. The communication challenges such as terahertz channel modeling, information encoding and protocols for nanosensor networks are presented. Designing nanoscale nanoantenna is presented in [93]. The authors numerically analyzed the performance of a graphene-based nanoantenna. Moreover, they calculated resonance frequency of the nanoantenna as a function, both analytically and by simulation. The radiation pattern of a graphene based nanoantenna is compared to an equivalent metallic antenna.

The energy consumption is a key issue in development of EM-based nanonetworks. In [94] an energy model is proposed for self-powered nanodevices. The model captures the correlation between the energy harvesting and the energy consumption processes. A mathematical framework is developed to obtain the probability distribution of the nanodevice energy and to investigate the end-to-end successful packet delivery probability, the end-to-end packet delay, and the throughput in nanonetworks.

In [91] massive multicore architectures are presented, the architecture is based on a wireless communication capabilities at the core level. They pointed out that designing nanoscale chip is possible by using graphene-based planar antennas. Moreover, the authors presented different methods that use wireless links, such as photonic-, wireless- and graphene-enabled (nanoscale) wireless communication.

In [4] the authors have introduced a physical layer aware MAC protocol for electromagnetic nanonetworks entitled PHLAME. This protocol is built on EM-communication scheme based on the exchange of femtosecond-long pulses spread in time. PHLAME protocol aims to minimize the interference in the nanonetwork and maximize the probability of successfully decoding the received information. The evaluation of the protocol has showed that it is able to support densely populated nanonetworks by exploiting the peculiarities of the Terahertz band.

## 5.5 Evaluation study

The topology used in designing Nano-NoC is depicted in Figure 5.5. Every nanoPE is coupled with a nanorouter (nanonode). It is in charge of aggregating and processing the information coming from nanoPEs as well as controlling their behavior by means of short control packets.

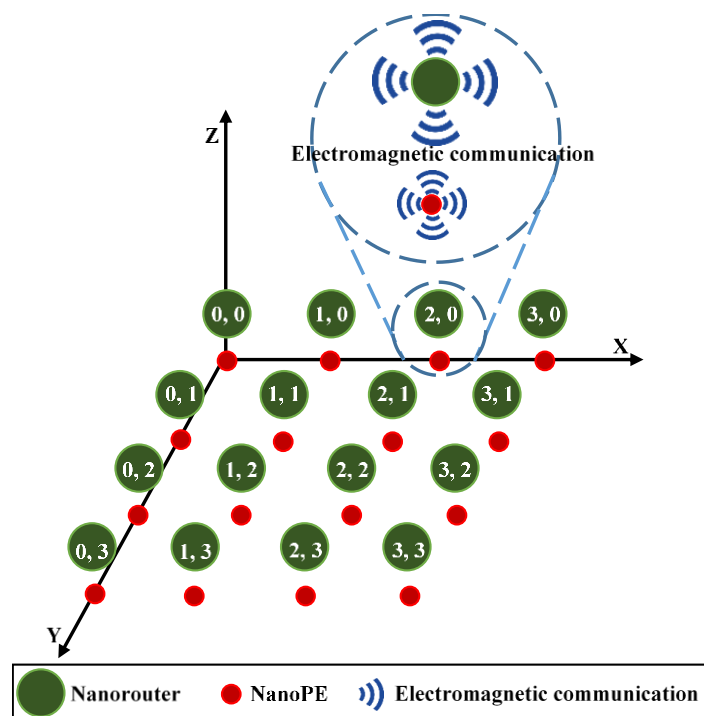


Figure 5. 5 Mesh-like Nano-NoC topology

### 5.5.1 Simulation parameters and metrics

The performance of a Nano-NoC is evaluated by the throughput, the average latency, and the energy consumption. To evaluate the energy consumption of these architectures, the model proposed in [95] is used. This model estimates the energy consumed by each bit traversed from one nanorouter to another. The total energy required to send one packet through the network can be decomposed into the energy consumed per hop as follows [95]:

$$E_{bit}(l) = \left(\frac{4\pi f_0}{c}\right)^2 \frac{N_0 SNR}{\log_2(1+SNR)} l^2$$

where  $f_0$  is the design center frequency, which is  $3.00E + 12 \text{ Hz}$  for the parameter related to behavior of electromagnetic interconnection in nanoscale;  $c$  is the light speed in the vacuum,  $c = 2.9979E + 08 \text{ m/s}$ ;  $SNR$  is constant signal-to-noise ratio guaranteed at the receiver,  $SNR = 10$ ;  $l$  is the distance. In simulations  $N_0$  is a constant, which could be calculated by  $N_0 = k_B \cdot T_0$ , where  $k_B$  is a Boltzmann constant  $k_B = 1.38E - 23$ ,  $T_0 = 296 \text{ K}$  (Kelvin). Thus,  $N_0 = 4.08672E - 2$ . Simulation parameters are presented in following table:

| Parameter                                  | Value         |
|--|---------------|
| Simulation duration                        | 4 s           |
| Number of nanonodes                        | from 4 to 625 |
| Pulse energy                               | 100 pJ        |
| Pulse duration                             | 100 fs        |
| Pulse Interarrival Time                    | 10 ps         |
| Packet size                                | 128 bytes     |
| Packet generation time interval per source | 0.2 s         |

|   |          |
|---|----------|
| Distance between non-diagonal neighboring nanorouters | 0.1 mm   |
| Distance between a nanoPE and the nearest nanorouter  | 0.008 mm |

**Table 5. 1 Simulation parameters for evaluation Nano-NoC**

The 2D mesh topology and four traffic patterns, such as Transpose, Bit-Reversal, Shuffle, and Uniform are considered. It is worth noting that traffic pattern models could be classified into two categories: synthetic and realistic. Realistic traffic pattern models are traces of application execution onto NoCs. It is common to evaluate NoC architectures by using traffic from real applications. Synthetic traffic models that most widely used for the analysis of energy consumption and latency are Uniform, Bit-Complement, Shuffle, Bit-Reversal, Hotspot and Self-Similar traffic patterns [84]. Several traffic pattern models are briefly described below, which we have used in our simulations:

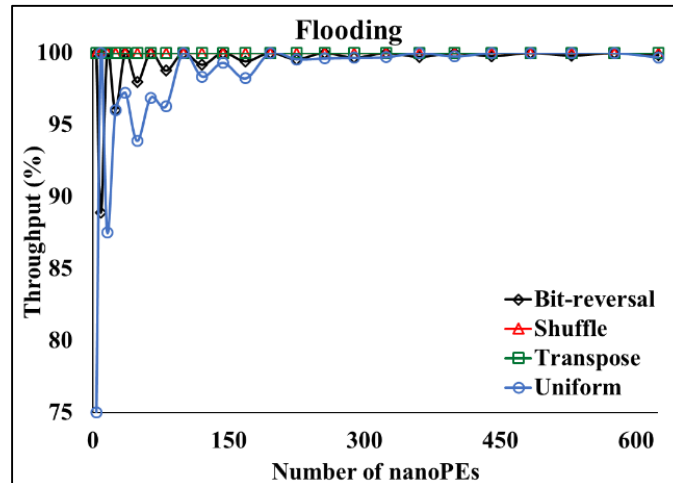
- *Uniform*. Each node sends messages to other nodes with equal probability. The destination nodes are chosen at random manner using a uniform probability distribution function.
- *Transpose*. Each node sends messages only to a destination with high/low half its own mapped address. The source with address  $(n_1, n_2, \dots, n_{m-1}, n_m)$  communicates with the destination node, whose address is given by  $(n_{m/2}, n_{(\frac{m}{2})+1}, \dots, n_m, n_1, n_2, \dots, n_{(\frac{m}{2})-1})$ .
- *Bit-Reversal*. Each node sends only node whose return address is reversed bit by bit, i.e. destination address is given by  $(n_m, n_{m-1}, \dots, n_2, n_1)$  for the source  $(n_1, n_2, \dots, n_{m-1}, n_m)$ .

- *Shuffle*. Each node sends only node whose return address is shifted left by rotating a bit, i.e., for a source node  $(n_1, n_2, n_3, \dots, n_{m-2}, n_{m-1}, n_m)$  destination address defines as following:  $(n_m, n_1, n_2, \dots, n_{m-3}, n_{m-2}, n_{m-1})$ .

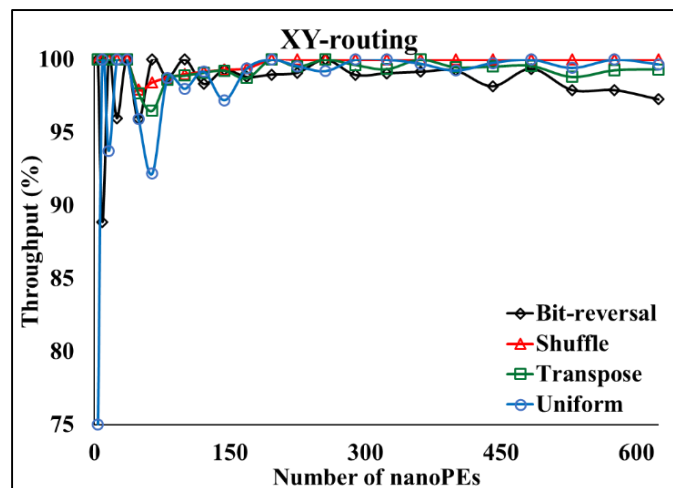
NoC performance depends on the routing protocols. In our work, we have used flooding algorithm and developed and integrated the XY-routing protocol into the simulator. Since we have described flooding well enough in other sections, XY-routing needs to be briefly described. XY-routing is one of the simplest and most commonly used routing algorithms in the Network-on-Chip (NoC). It is a static and deterministic routing algorithm, without deadlock. Let us consider  $s = (s_x, s_y)$  a node that contains a packet addressed to node  $d = (d_x, d_y)$ . In the XY routing algorithm, the X direction has higher priority. If the X of destination  $d$  is greater (resp. less) than the X of origin  $s$ , the next node is the node  $(s_x + 1, s_y)$  (resp.  $(s_x - 1, s_y)$ ) on the X-axis. Otherwise, the X's are equal and we compare the Y's: the next node is either  $(s_x, s_y + 1)$  or  $(s_x, s_y - 1)$  on the Y-axis. This algorithm is applied recursively to compute the route from a source to a destination [85].

### 5.5.2 Simulation results

We evaluated the throughput, the average latency, and the energy consumption by varying the number of nanonodes, the transmission range while using flooding and XY-routing techniques. Figure 5.6 compares the throughput while using different traffic patterns and by varying the number of nanonodes. The transmission range of nanorouters is equal to the distance between neighboring nanorouters.



(a)

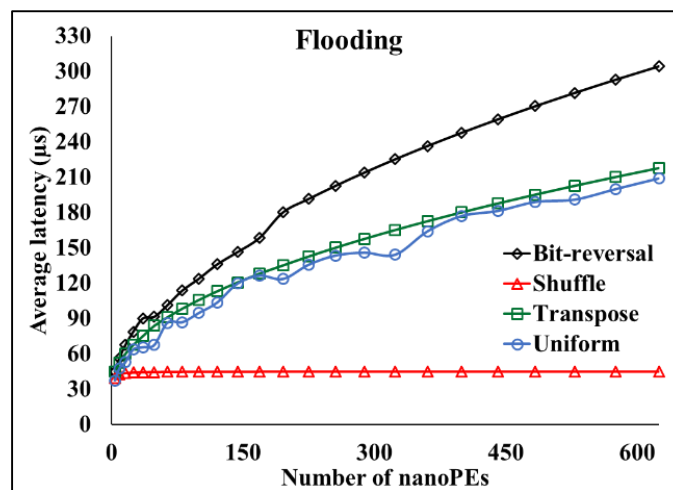


(b)

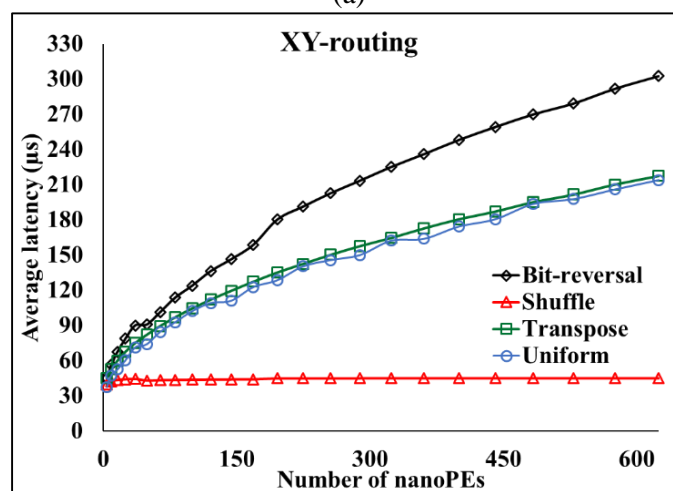
**Figure 5.6 The throughput comparison according to number of nanonodes when using different traffic patterns**

In this case, the transmission range of nanorouters covers one nanoPE and at least two neighboring nanorouters. In case of using both routing techniques, the results show that the throughput become higher with increasing number of nanonodes in case of Bit-Reversal and Uniform traffic patterns. In case of using Shuffle and Transpose traffic patterns all packets are arrived to destination nanoPE. When XY-routing is used, as illustrated in Figure 5.6(a), the higher throughput is observed for all traffic patterns. Similar results are shown in Figure 5.6 (b), by increasing number of nanonodes the throughput gets higher values. Moreover, the simulation results demonstrate that the distance between source and destination nanoPE affects the throughput. The throughput

will be low if the average length of sources and destinations is small. The selection method of sources and destinations is random in Uniform traffic pattern, therefore, there is a possibility that the average path length could be long. Distance between source and destination nanoPE is longer in Bit-Reversal traffic pattern than other traffic patterns used in the simulations. Thus, we can conclude that the average path length affects the throughput and it should be considered in designing Nano-NoC. Transpose and Shuffle traffic patterns provide better throughput.



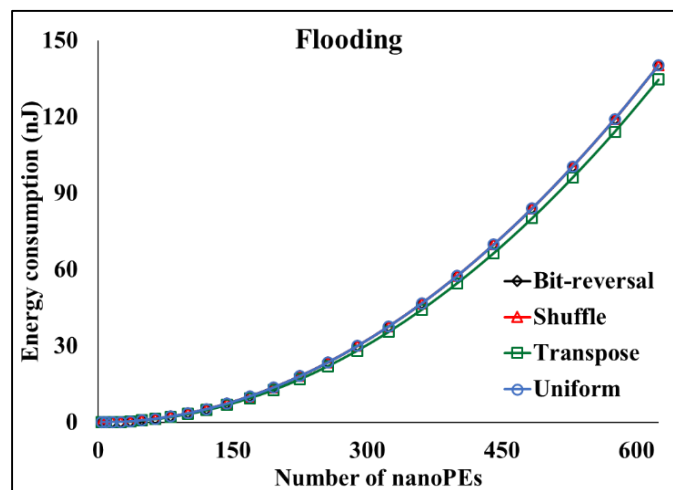
(a)



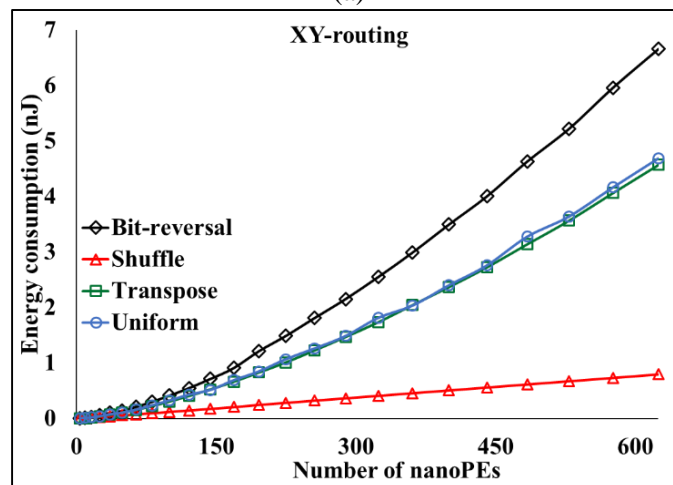
(b)

Figure 5. 7 The latency comparison according to number of nanonodes when using different traffic patterns

Fig. 5.7 demonstrates comparison of the average latency in Nano-NoCs designed with different traffic patterns. Horizontal and vertical axis illustrates the number of nanonodes and the average latency in microseconds respectively. It should be noted that the average latency is same when flooding (Fig. 5.7(a)) and XY-routing (Fig. 5.7(b)) mechanisms are used. It is due to the fact that the number of hops is equal for any pair of source-destination (respectively taken by rule of traffic pattern). It could be seen that the Shuffle traffic pattern gives the best results, because the distance between source and destination pairs are located close to each other.



(a)

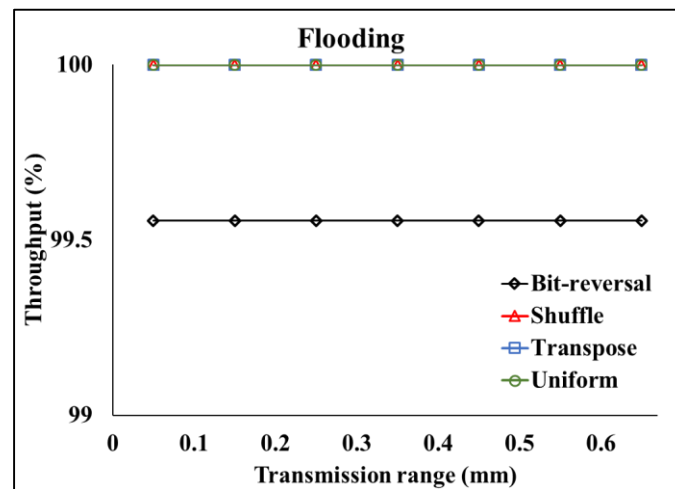


(b)

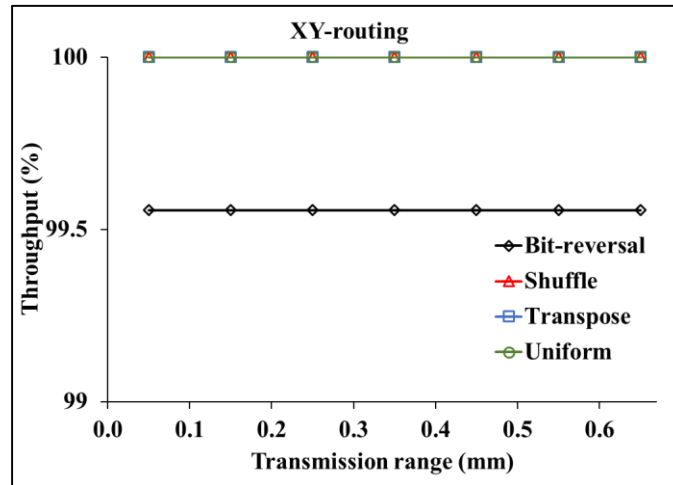


**Figure 5. 8 The energy consumption comparison according to number of nanonodes when using different traffic patterns**

The energy consumption is calculated when packets are transmitted and received for each nanodevice. Fig. 5.8 presents comparison of the energy consumption with different parameters. Vertical and horizontal axis demonstrate the energy consumption ( $nJ$ ) and number of nanonodes, respectively. The energy consumption is almost same for all traffic patterns in case of flooding as shown in Fig. 5.8(a). When XY-routing is used, energy is much less consumed compared to the flooding. Fig. 5.8(b) demonstrates that nanodevices spent more energy with Bit-Reversal traffic pattern. The less energy consumption is achieved when using Shuffle traffic pattern, because different number of TX and RX in routing mechanism (it is less in XY-routing than flooding).



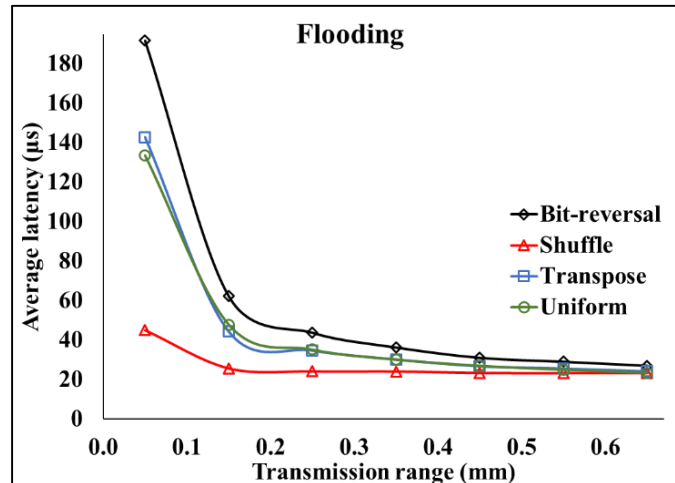
(a)



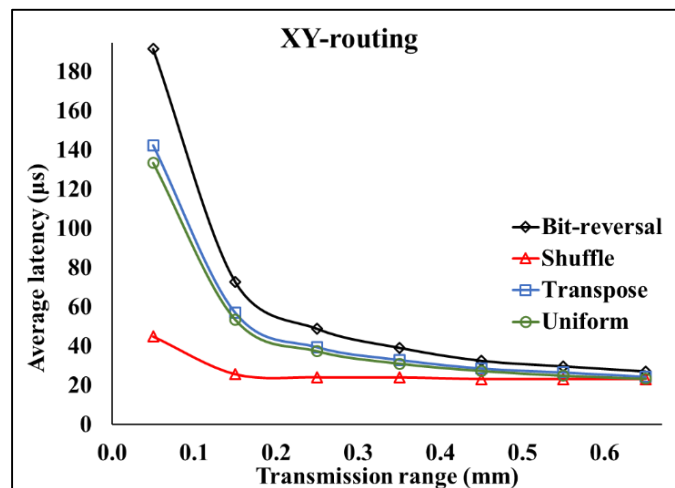
(b)

**Figure 5. 9 Throughput comparison according to transmission range**

Moreover, simulations are conducted with different transmission ranges by fixing number of nanonodes (225) and nanorouters (225) in 15x15 mesh-network. Fig. 5.9 demonstrates that varying transmission range in nanonetworks with same number of nanonodes does not affect the throughput while using two types of routing mechanisms. Results for the throughput might be different when using Bit-Reversal, Shuffle, Transpose and Uniform traffic patterns. It could be seen in Fig. 5.9(a) and Fig. 5.9(b) that the throughput is same regardless to selected traffic pattern. It is due to the number of hops between source and destination. In case of using Uniform traffic pattern the throughput is different according to selected source and destination nanoPE. We observed the same throughput with different transmission ranges when Bit-Reversal traffic pattern is used; it is due to larger number of hops between sources and destinations. When Shuffle and Transpose traffic patterns are used, the throughput is near zero.



(a)

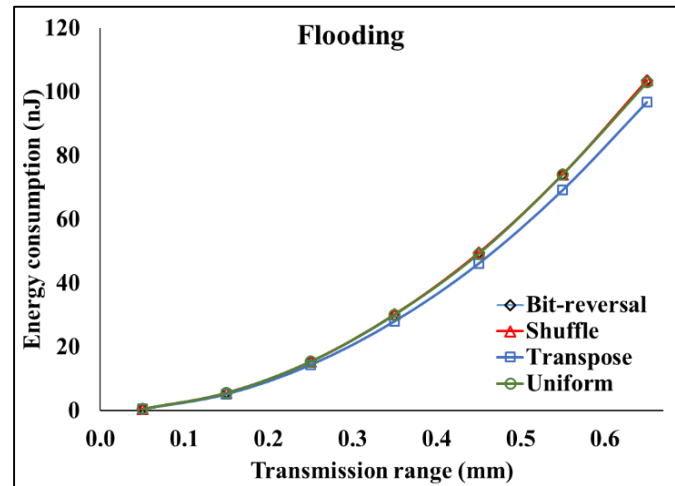


(b)

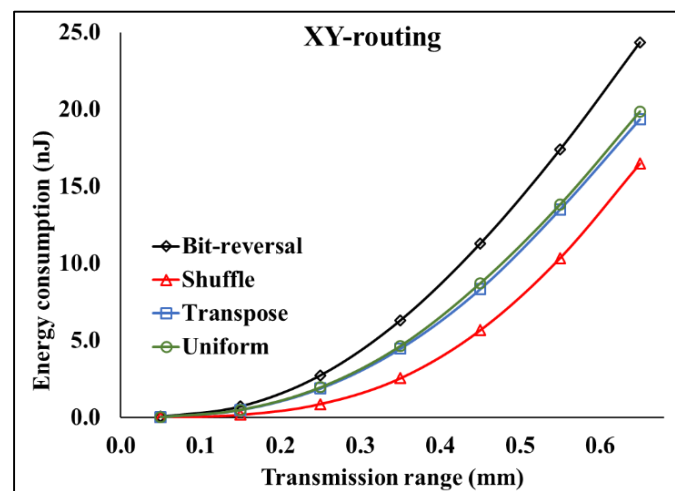
Figure 5.10 The average latency comparison according to transmission range

Figure 5.10 presents the average latency according to different transmission ranges. Flooding and XY-routing mechanisms have similar behavior regardless of the average latency as presented respectively in Figure 5.10(a) and Figure 5.10(b). It is due to the average delivery time of packets that is same for both routing techniques. A significant average latency with low transmission range is observed, especially when using Bit-Reversal, it is more than 180 microsecond ( $\mu s$ ). The average latency decreases for all traffic pattern by increasing transmission range, almost the same average latency with high (0.6 mm) transmission range. We can conclude that increasing transmission range

of nanorouters gives better results for the average latency, since packets are transmitted faster among nanonodes. However, increasing transmission range causes high energy consumption due to numerous useless transmissions and receptions.



(a)



(b)

Figure 5.11 The energy consumption comparison according to transmission range when using different traffic patterns

Figure 5.11 depicts the energy consumption while using the two routing algorithms and four traffic patterns. Theoretically, by increasing the transmission range, the energy consumption could be decreased. When using higher transmission range redundant transmissions and receptions are observed. Fig. 8(a) shows that the energy consumption

is almost same when flooding is used for all traffic patterns. It is due to active participation of nanorouters in transmitting and receiving packets. Fig. 8(b) depicts the energy consumption when XY-routing is used. It can be seen that while using Shuffle traffic pattern, the less energy consumption is achieved. When Bit-Reversal traffic pattern is used nanoPE spend more energy. Moreover, it should be noted that using XY-routing mechanism gives best results for the energy consumption, but optimal parameters should be selected to improve the throughput.

## 5.6 Conclusions

In this chapter, the performance of an EM-based Nano-NoC based on 2D Mesh-like topology for different classes of on-chip communication traffics are quantitatively compared and characterized. The throughput, the average latency, and the energy consumption of Nano-NoC are evaluated. Simulation results show that variation of transmission range does not affect the throughput. It remains constant because all generated packets by source nanoPEs are received by destination nanoPEs in case of Shuffle, Transpose, and Uniform patterns, but some packets drop is observed in the case of Bit-Reversal pattern, regardless of the variation of transmission range. Results show also that using XY-routing technique is more adapted to 2D mesh-like topology in Nano-NoC. The obtained results show that the generated traffic by the nanoPEs has a direct effect on the performance.

## Conclusions and perspectives

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## 6.1 Summary

The work presented in this thesis deals with investigation of information dissemination in electromagnetic-based wireless nanosensor networks and network on a chip in nanoscale.

We have studied different types of wireless networks, and particularly, EM-based wireless nanosensor networks and networks on a chip in nanoscale in the chapter 2. Whole description of EM-based WNSNs, including applications, communication mechanisms, its architecture and nanodevices are presented in the subchapter 2.8. Then we have introduced the WNSNs for embedded system design, it includes Nano-NoC concepts for SoC design. And finally, we presented simulation tools for EM-based WNSNs.

Efficient flooding algorithm and adapted transmission range approach are presented in the chapters 3 and the chapter 4, respectively. Information dissemination in Nano-NoC for SoC design is studied in the chapter 5. The main approach of these approaches to provide adequately performance of WNSN and Nano-NoC. Performance evaluations are include main cost metrics, such as latency, packet delivery ratio and energy consumption. Due to these networks intended to deploy in nanoscale, controlling information dissemination is difficult issue. Therefore, we have supposed that each nanodevice have ability to perform receiving and broadcasting information, store very small information etc.

In the chapter 3, we have proposed method of reducing number of transmission and receptions based on counter-based scheme. Redundant rebroadcasts are main issue in all

kind of wireless networks, in particular, WNSNs. Redundant rebroadcasts are also cause of the energy hunger. We have adapted counter-based scheme for WNSNs; the scheme works base on local information about neighbors about nanodevice. Every nanodevice rebroadcasts or discards information in consideration of threshold. Nanodevices rebroadcast or discard information depending on threshold value. However, in dynamic networks, it is difficult even impossible to determine a priori these parameters. For rebroadcast decision, nanodevices need the number of received same messages during fixed time slot. In the end of the fixed time, intermediate nanonodes decide rebroadcasting received packets if only the counter of the packet is low. Counting same messages might help to define nanonodes about the network density. If counter gets high value, whole network or part of this network might be dense. In this scheme threshold should be tuned carefully. Sparse network suffers from high threshold, since nanonodes could receive same packets rarely. Choosing high threshold affects overall evaluations of dense network; in this case, counter-based scheme might not be effective in reducing redundant rebroadcasts. We have varied network density, transmission range, network load and threshold to investigate network behavior. In the end of the chapter we have presented results; obtained results compared with basic flooding mechanism.

In the adaptive transmission range approach, we also have been considered solution of reducing excessive transmissions, wherein efficiency of the approach should not decrease performance of average latency and packet delivery ratio. The main goal of proposing the approach is to normalize the main metrics of network performance. To achieve this objective, we mainly considered network density. For example, setting a large transmission range to nanodevices, increases the number of neighbors, probability of high collision and might contribute higher progress. If the transmission is successful, it



guarantees low latency with high throughput. The results have shown efficiency of adaptive transmission range approach. By using the approach, we have decreased broadcasting, at the same time we have showed efficiency of the approach in context of throughput and latency according to a network density. For example, when we fixed the transmission range of nanonodes the throughput was very low in sparse networks. For example, when we have simulated a sparse network of 100 nanodevices, average 80% packets are received by destination node with fixed transmission range (0.01 cm). In dense (500 nanodevices) network 100% of packets are delivered when we fixed transmission range to 0.004 cm. We then presented results of adaptive transmission range approach that allows nodes to select the best suitable transmission range in order to increase network connectivity. Result showed that this approach provides a good throughput while minimizing latency.

We have presented Nano-NoC concepts for SoC design are in the chapter 5. In this chapter, the performance EM-based on-chip interconnect for SoCs has been evaluated. The objective of conducting the investigation is to design and to investigate performance of Nano-NoC. We have presented components and architecture of NoC, communication methods. We first have investigated existing NoC concepts and architectures. Then we have presented Nano-NoC design and its performance. Performance evaluations are conducted in consideration of average latency, throughput and energy consumption. We have compared flooding and XY-routing mechanisms using different network densities and traffic patterns, such as Uniform, Bit-Reversal, Transpose and Shuffle. Results for the cost metrics of any network are depicted in figures respectively. Results have shown that the use of flooding mechanisms gives best results for average latency and throughput. However, in this case, requirement to energy drastically increased. In case of the use of

XY-routing mechanism, like any network, the mechanism has proved its efficiency to energy consumption, other metrics get acceptable values.

## 6.2 Future work

Wireless nanosensor networks will enable many awaited applications in different areas of vital activity, ranging from healthcare to security, industrial development and environmental protection. However, nanosensor devices and WNSNs are in their early stage. Information and communication technologies play important role in developing and implementing them in vital activity. Currently, a lot of research are conducting of development of nanosensor devices in the field of science. At the same time, nanodevices of WNSNs should able to connect with other networks, such as intranet, internet, etc.

Since in this thesis includes EM-based nanocommunication based WNSNs and Nano-NoC aspects, in the future we will continue working on this field to propose some solutions of its issues.

Our future research directions are summarized as follows:

- Information dissemination protocols, including geometric-based and network topology based protocols should be adapted in context of EM-based nanocommunication.
- Implementing critical transmission range algorithm for WNSNs.
- Proposing efficiency architecture for Nano-NoC and evaluate its performance;
- Implementing energy model in Nano-Sim for EM-based nanocommunication.
- Implementing graphical interface for simulations of WNSNs.

Moreover, we have planned working on molecular (chemical) nanocommunication based nanosensor networks, since this is the more suitable mechanism for organic and biological objects. Our future objective includes investigate molecular communication, its architecture and evaluate performance.

## **List of personal publications**

### **International conferences**

- [1] O. Yalgashev, M. Bakhouya, A. Chariete and J. Gaber, "Electromagnetic-based Nanonetworks Communication in SoC Design" in the 2015 High Performance Computing & Simulation (HPCS 2015), Amsterdam, the Netherlands, 2015.
- [2] O. Yalgashev, M. Bakhouya, J. Gaber, M-A. Manier, "Adaptive Transmission Range Control for Electromagnetic-based Broadcasting in Nanonetworks" in The 5th International Symposium on Frontiers in Ambient and Mobile Systems (FAMS), London, 2015.
- [3] O. Yalgashev, M. Bakhouya, A. Chariete and J. Gaber, "Performance Evaluation of Nano-On-Chip Interconnect for SoCs" in the 2015 International Conference on High Performance Computing & Simulation (HPCS 2014), Bologna, Italy, 2014.

### **Chapter**

- [4] O. Yalgashev, M. Bakhouya, A. Nait-Sidi-Moh and J. Gaber, "Wireless Sensor Networks Basics and Fundamentals", book chapter of "Cyber-Physical System Design with Sensor Network Technologies", IET, 2015, accepted to appear

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## **Abstract:**

Nanocommunication is a new paradigm that enables connectivity at the nanoscale through molecular, electromagnetic, acoustic, or nanomechanical mechanisms. The general context of this thesis concerns wireless nanosensor networks and nanonetworks on chips. More precisely, the thesis deals with interconnection architectures and communication protocols in the terahertz band. The existing network architectures and communication protocols should be revisited taking into account the communication mechanisms at the nanoscale.

First, dissemination approaches in the context of wireless nanosensor networks are addressed. An efficient broadcasting approach is presented and the simulation performance results with Nano-Sim and NS3 show that the proposed scheme is superior to flooding, especially in the cases of excessive broadcasts.

Second, we investigated the impact of transmission ranges on the performance of broadcast mechanisms based on electromagnetic waves at the nanoscale. Adaptive transmission range of electromagnetic-based communication approaches are proposed. Simulations are conducted with fixed and adaptive transmission ranges to show the efficiency of the proposed approaches in terms of throughput and latency according to the network density. The third part addresses the hypothesis of using EM-based nanonetwork as an on-chip interconnect for SoCs.

**Keywords:** nanocommunication, Téraherz band, Wireless nanosensor networks, nanonetwork on chip, Nano-Sim, NS3.

## **Résumé :**

La nanocommunication est un nouveau paradigme qui permet de communiquer à l'échelle nanométrique, via des mécanismes moléculaires, électromagnétiques, acoustiques, ou nano-mécaniques. Le cadre général de cette thèse concerne les réseaux de nanocapteurs sans fil et les nanoréseaux sur puce. Plus précisément, il s'agit des architectures d'interconnexion et des protocoles de communication dans la bande de fréquence des Téraherz. En effet, les architectures réseaux et les protocoles de communication existants doivent être repensés en tenant compte des mécanismes de communication à l'échelle nanométrique.

En premier lieu, nous nous sommes focalisés sur la nécessité de développer des approches de diffusion efficaces dans le contexte des réseaux de nanocapteurs sans fil. Une approche de diffusion efficace, issue d'une adaptation d'un protocole de la famille des protocoles d'inondation probabilistes, est présentée et son efficacité et validée par simulations à l'aide de Nano-Sim et NS3.

En second lieu, une étude approfondie de l'impact des portées de transmission sur les performances du mécanisme de diffusion basé sur les ondes électromagnétiques à l'échelle nanométrique a été effectuée. Les résultats des simulations montrent que l'adaptation des portées des nano-nœuds permet de contrôler le mécanisme d'inondation et de réduire les redondances des paquets tout en augmentant les débits. Une approche adaptative de sélection de portées de transmission contrôlée au niveau des nano-nœuds est proposée. En dernier lieu, nous nous sommes attaqués à un troisième défi en examinant ce nouveau paradigme de nanocommunication dans le contexte de la conception des nanoréseaux sur puce (Network on Chip, NoC).

**Mots clés :** nanocommunication, bande de fréquence des Téraherz, nanocapteurs sans fil, nanoréseaux sur puce, Nano-Sim, NS3.

SPIM



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## Thèse de Doctorat



école doctorale sciences pour l'ingénieur et microtechniques  
UNIVERSITÉ DE TECHNOLOGIE BELFORT-MONTBÉLIARD

# **TOWARDS NANOSCALE INTERCONNECT FOR SYSTEM-ON-CHIP AND WIRELESS NANOSENSOR NETWORKS**

 **Olimjon YALGASHEV**