Doctoral Thesis

Energy Efficient Data Collection in Body Area Nanonetworks

by

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Abstract

Body Area Nanonetworks (BANNs) are an important class of emerging nanonetworks, where tiny nano-nodes move in human body and can communicate with each other over peer-to-peer wireless links. Since they can provide inexpensive and continuous health monitoring services, BANNs hold great promises for many important biomedical applications in immune and drug delivery systems. In these systems, it is critical for nano-nodes to collect real-time data information. However, the constraint of extremely limited energy stored in nano-nodes poses a great obstacle to the future applications of BANNS. Thus, a comprehensive study on the energy efficient data collection schemes in BANNs is of great importance for supporting their applications.

We first propose a lightweight data collection scheme under a simple yet efficient scenario with multiple nano-nodes and only one nano-router in BANNs. In the scheme, we employ a sleep/wake-up mechanism to avoid unnecessary energy consumption when no eternal request comes. With a careful consideration of both node available energy and transmission energy consumption, we then design a new node selection strategy to further reduce the energy consumption in the data collection process. We further conduct extensive simulations for both the proposed data collection scheme and the benchmark greedy scheme to validate energy efficiency of our scheme as well as to illustrate the impacts of network parameters on data collection performance.

We further propose a new energy efficient data collection scheme under a complex scenario with multiple nano-nodes and nano-routers in BANNs. In the scheme, we first categorize data as emergent data and normal data with a careful consideration of the energy constraints. Based on such classification, we then generate distinct packets and assign different priorities to them. In BANNs, the normal data is usually sent regularly, while the emergent data is sent immediately. Extensive simulations are also provided to validate energy efficiency of our scheme in comparison with other benchmark greedy scheme, and to illustrate the impacts of network parameters on data collection.

Finally, we propose a relay-based energy-efficient data collection scheme with the minimum energy coding. Under the scheme, we derive the maximum nano-node density for reliable communication in BANNs, and also conduct density-dependent reliability analysis. Both rate-energy and delay-energy tradeoffs are further investigated with constant codebook size and constant Hamming distance, respectively. We also provide extensive simulations to validate our scheme.

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Contents

List of Figures

Chapter 1

Introduction

In this chapter, we first introduce the background of our study and some related terms (like nanonetworks, nano-machine, body area nanonetworks, etc). Then we describe the motivations of this thesis, and the outline of this thesis.

1.1 Background

Recent advancements in nano-technology have boosted the growth in small-scale communication. Specially, the wireless nanonetworks are a class of new small-scale communication paradigm. The emergence of nano-technology paves the path of developing nano-machines to perform very simple and specific tasks at nano-level such as computing, data storing, sensing and actuation [1] for diversified applications in biomedical, environment science, industrial development, food science, military, etc [2, 3]. The nano-machines can be developed for performing highly-sophisticated tasks such as recognizing and destroying tumors cells via penetration of sensitive body sites including the spinal cord, gastrointestinal, etc [4]. It is of great importance to promote nono-machines to communicate with each other such that they can make decisions efficiently for complex diseases [5]. The nano-machines with limited capabilities perform tasks by forming an interconnected nanonetwork. Such communication among the nano-machines for healthcare applications introduces a new paradigm called Body Area Nanonetworks (BANNs) [6].

Despite the fact that nano-device technology has been witnessing great advancements, enabling the communication among nano-machines is still a major challenge. The traditional communication protocols are not applicable to enable the nodes to communicate among themselves at the nano-scale, these conventional systems need to undergo extensive revisions. Based on the preferred transmission medium, different communication paradigms have been proposed over time, which include acoustic, nano-mechanical, molecular, and electromagnetic (EM) [7].

For practical reasons, only specific paradigms can be applied to specific scenarios. For example, due to a very high absorption coefficient of acoustic waves in bones and muscle fiber, using acoustic paradigm based communication is impractical [8]. Nano-mechanical communication requires physical contact between transmitting and receiving nano-machines, which is not always possible. The molecular and EM communication paradigms have been very promising [6] with molecules as the encoder, transmitter and receiver of information in molecular communication [9] and EM waves as the communication means among nano-machines in EM communication. One of the mechanisms being comprehensively investigated is molecular communication [10], which is based on the exchange of molecules to transmit information. However, there are still many fundamental challenges to address, including the development of mechanisms to overcome the very long latency in molecular systems or the potential interference with biological molecular processes. On the other hand, molecular communication enables nano-machines to communicate with each other through using biocompatible molecules as communication carriers, which makes molecular communication a feasible option for BANNs. However, molecular communication is generally slow and more error-prone in comparison to electromagnetic communication making molecular communication less suitable for real-time healthcare applications [11].

Recent developments in graphene-based nano-electronics, nano-photonics and nano-plasmonics [12] enable electromagnetic (EM) communication among nano-devices in the Terahertz (THz) band (0.1-10 THz) [13, 14]. Electromagnetic communication, particularly in the THz frequency band, will be the primary driver in realizing nano-nodes functionalities because nano-nodes collect and process a variety of useful information by communicating with one another [15]. Also, their limited processing and storage requires them to transfer data to another network for further processing. Communication in all its forms will require energy, therefore, the energy problem is particularly important.

However, the nanosensors in BANNs are usually limited in size (from 1 nm to 100 nm), resulting in that energy supplying devices can hardly be utilized. Therefore, these networks are extremely energy constrained in general, which significantly reduces their lifetime, and thus may hinder their wide application and further development [16, 17].

1.1.1 Related Terms

We introduce the following terms related to the BANNs.

We first introduce **nano-machine**. Nano-technology enables the miniaturization and fabrication of devices in a scale ranging from 1 to 100 nano-meters [1]. At this scale, a nano-machine can be considered as the most basic functional unit. In general terms, we define a nano-machine as a device, consisting of nano-scale components, able to perform a specific task at nano-level, such as communicating, computing, data storing, sensing and actuation. The tasks performed by one nano-machine are very simple and restricted to its close environment due to its low complexity and small size.

There are three different approaches for the development of nano-machines as depicted in Fig. 1-1. In the topdown approach, nano-machines are developed by means of downscaling current microelectronic and micro-electro-mechanical technologies without atomic level control. In the bottom-up approach, the design of nano-machines is realized from molecular components, which assemble themselves chemically by principles of molecular recognition arranging molecule by molecule. Recently, a third approach called bio-hybrid is proposed for the development of nano-machines [18]. This approach is based on the use of existing biological nano-machines, such as molecular motors [19], as components or models for the development of new nano-machines.

In the future, nano-machines will be obtained following any of these three ap-

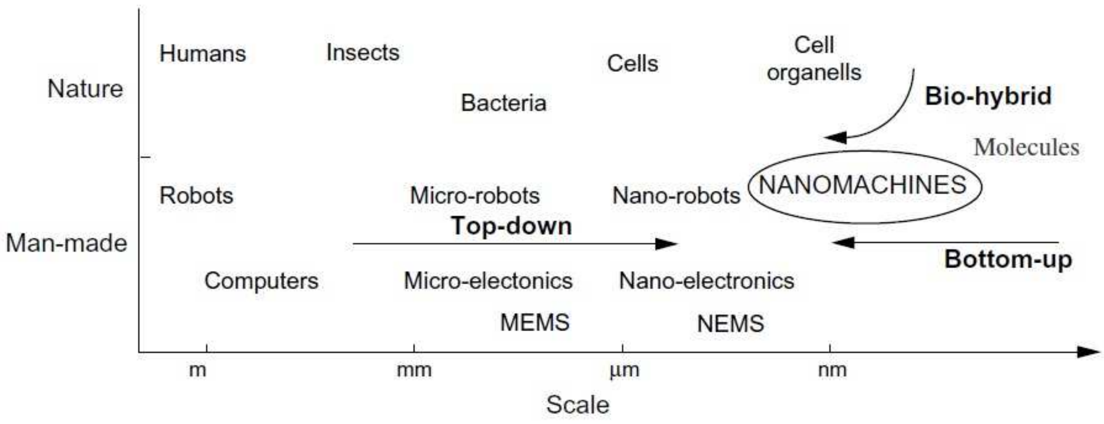

Figure 1-1: Approaches for the development of nano-machines

proaches. However, the existence of successful biological nano-machines, which are highly optimized in terms of architecture, power consumption and communication, motivate their use as models or building blocks for new developments.

- Top-down approach

  Recently, newest manufacturing processes, such as the 14 nm lithographic process, have made the integration of nano-scale electronic components in a single device possible. The top-down approach is focused on the development of nano-scale objects by downscaling current existing micro-scale level device components. To achieve this goal, advanced manufacturing techniques, such as electron beam lithography and micro-contact printing, are used.

  Resulting devices keep the architecture of preexisting micro-scale components such as microelectronic devices and micro-electro-mechanical systems (MEMS). Nano-machines, such as nano-electromechanical systems (NEMS) components, are being developed using this approach [20]. However, the fabrication and assembly of these nano-machines is still at an early stage. So far, only simple mechanical structures, such as nano-gears [21], can be created following this approach.

- Bottom-up approach

  In the bottom-up approach, nano-machines are developed using individual molecules as the building blocks. Recently, many nano-machines, such as molecular differential gears and pumps, have been theoretically designed using a discrete number of molecules. Manufacturing technologies which are able to assemble nano-machines molecule by molecule do not exist, but once they do, nano-machines could be efficiently created by the precise and controlled arrangement of molecules. This process is called molecular manufacturing. Current development of nano-machines using this bottom-up approach, such as molecular switches and molecular shuttles, are based on self-assembly molecular properties [22].

- Bio-hybrid approach

  Several biological structures found in living organisms can be considered as nano-machines. Most of these biological nano-machines can be found in cells. Biological nano-machines in cells include: nano-biosensors, nano-actuators, biological data storing components, tools and control units. Several biological nano-machines are interconnected in order to perform more complex tasks such as cell division. The resulting nanonetwork is based on molecular signaling. This communication technique is also used for inter-cell communication allowing multiple cells to cooperate to achieve a common objective such as the control of hormonal activities or immune system responses in humans.

  The bio-hybrid approach proposes the use of these biological nano-machines as models to develop new nano-machines or to use them as building blocks integrating them into more complex systems such as nano-robots. Following this approach, the use of bacteria as controlled propulsion mechanisms for the transport of micro-scale objects [23].

- Nano-machine architecture

  A nano-machine could consist of one or more components, resulting in different levels of complexity, which could be from simple molecular switches to nano-robots [24]. The most complete nano-machines will include the following architecture components:

(1) *Control unit.* It is aimed at executing the instructions to perform the intended tasks. To achieve this goal, it can control all the other components of the nano-machine. The control unit could include a storage unit, in which the information of the nano-machine is saved.

(2) *Communication unit.* It consists of a transceiver able to transmit and receive messages at nano-level, e.g., molecules.

(3) *Reproduction unit.* The function of this unit is to fabricate each component of the nano-machine using external elements, and then assemble them to replicate the nano-machine. This unit is provided with all the instructions needed to realize this task.

(4) *Power unit.* This unit is aimed at powering all the components of the nano-machine. The unit will be able to scavenge energy from external sources such as light, temperature and store it for a later distribution and consumption.

(5) *Sensor and actuators.* Similar to the communication unit, these components act as an interface between the environment and the nano-machine. Several sensors or actuators can be included in a nano-machine, e.g., temperature sensors, chemical sensors, clamps, pumps, motor or locomotion mechanisms.

Currently such complex nano-machines cannot be built. However, there exist systems found in the nature, such as living cells, with similar architectures. According to the bio-hybrid approach these biological models, i.e., the cells, can be used to learn and understand the principles governing the operation of nano-machines and their interactions. This knowledge is expected to contribute to the development of new bio-inspired nano-machines and systems for specific purposes. In Fig. 1-2, we show a component mapping between a generic architecture of a nano-machine and a living cell, including its biological nano-machines.

We then introduce **nanonetwork**. A nanonetwork or nano-scale network is a set of interconnected nano-machines (devices a few hundred nano-meters or a few micrometers at most in size), which are able to perform only very simple tasks such as

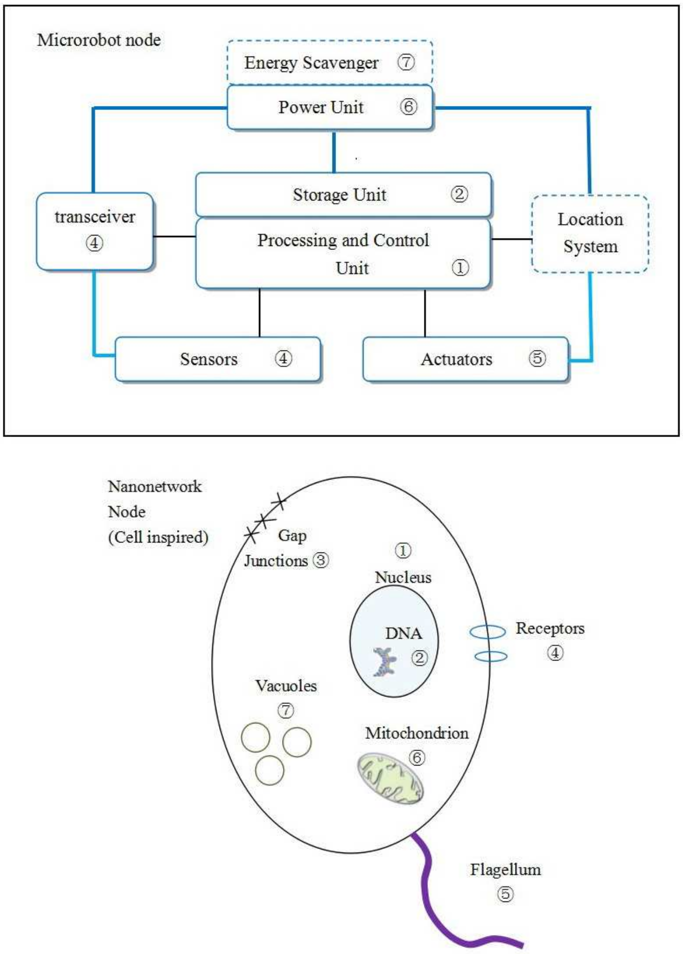

Figure 1-2: Functional architecture mapping between nano-machines of a micro or nano-robot, and nano-machines found in cells.

computing, data storing, sensing and actuation [1]. Nanonetworks are expected to expand the capabilities of single nano-machines both in terms of complexity and range of operation by allowing them to coordinate, share and fuse information. Nanonetworks enable new applications of nano-technology in the biomedical field, environmental research, military technology and industrial and consumer goods applications.

Nanonetworks will enable the interaction with remote nano-machines by means of broadcasting and multihop communication mechanisms. Classical communication paradigms need to be revised for the nano-scale. Communication in the nano-scale can be realized through nano-mechanical, acoustic, electromagnetic and chemical or molecular communication means [1]. Nano-mechanical communication is defined as the transmission of information through mechanical contact between the transmitter and the receiver. In acoustic communication, the transmitted message is encoded using acoustic energy, i.e., pressure variations. Electromagnetic communication is based on the modulation of electromagnetic waves to transmit information. Molecular communication can be formally defined as the use of molecules as messages between transmitters and receivers.

For the time being, it is still not clear how these nano-sensor devices will communicate. We envision two main alternatives for communication in the nano-scale, namely, molecular communication and nano-electromagnetic communication.

- Molecular communication:

  It is defined as the transmission and reception of information encoded in molecules [1, 25]. Molecular transceivers will be easy to integrate in nano-devices due to their size and domain of operation. These transceivers are able to react to specific molecules and to release others as a response to an internal command or after performing some type of processing. The released molecules are propagated either following spontaneous diffusion in a fluidic medium (diffusion-based), through diffusion in a fluidic medium whose flow is guided (flow-based) [26], or through active carriers that transport them through pre-defined pathways (walkway-based). This radically different communication paradigm necessitates novel channel models [27], network architectures [19] and communication protocols.

- Nano-electromagnetic communication:

  It is defined as the transmission and reception of electromagnetic radiation from components based on novel nano-materials [28]. Recent advancements in molecular and carbon electronics have opened the door to a new generation of electronic nano-components such as nano-batteries, nano-memories, logical circuitry in the nano-scale and even nano-antennas. From a communication perspective, the unique properties observed in novel nano-materials will decide on the specific bandwidths for emission of electromagnetic radiation [29], the time lag of the emission, or the magnitude of the emitted power for a given input energy. All these entail a fundamental change in the current state of the art of analytical channel models [30], network architectures and communication protocols [31].

Next, we introduce the **Internet of Nano-Things**. Nano-technology is enabling the development of devices in a scale ranging from one to a few hundred nano-meters. At this scale, a nano-machine is defined as the most basic functional unit, integrated by nano-components and can perform simple tasks such as sensing or actuation. Coordination and information sharing among several nano-machines will expand the potential applications of individual devices in terms of both complexity and range of operation [1, 14]. The resulting nanonetworks will be able to cover larger areas, to reach unprecedented locations in a non-invasive way, and to perform additional in-network processing. Moreover, the interconnection of nano-scale devices with classical networks and ultimately the Internet defines a new networking paradigm, to which we further refer as the Internet of Nano-Things.

The Internet of Nano-Things begins at the networking of several nano-machines. Nanonetworks are not just downscaled networks, there are several properties stemming from the nano-scale that require us to totally rethink well-established networking concepts. In the following, the main challenges from the communication perspective are discussed in a bottom-up fashion, by starting from the physical nano-scale issues affecting a single nano-machine up to the nanonetworking protocols.

Regardless of the final application, we identify the following components in the network architecture of the Internet of Nano-Things:

Nano-nodes: these are the smallest and simplest nano-machines. They are able to perform simple computation, have limited memory, and can only transmit over very short distances, mainly because of their reduced energy and limited communication capabilities. Biological nano-sensor nodes inside the human body and nano-machines with communication capabilities integrated in all types of things such as books, keys, or paper folders are good examples of nano-nodes.

Nano-routers: these nano-devices have comparatively larger computational resources than nano-nodes and are suitable for aggregating information coming from limited nano-machines. In addition, nano-routers can also control the behavior of nano-nodes by exchanging very simple control commands (on/off, sleep, read value, etc.). However, this increase in capabilities involves an increase in their size, and this makes their deployment more invasive.

Nano-micro interface devices: these are able to aggregate the information coming from nano-routers, to convey it to the microscale, and vice versa. We think of nano-micro interfaces as hybrid devices able both to communicate in the nano-scale using the aforementioned nano-communication techniques and to use classical communication paradigms in conventional communication networks.

Gateway: this device enables the remote control of the entire system over the Internet. For example, in an intrabody network scenario, an advanced cellphone can forward the information it receives from a nano-micro interface in our wrist to our healthcare provider. In the interconnected office, a modem-router can provided this functionality.

Finally, we introduce the **Body Area Networks**. A body area network (BAN), also referred to as a wireless body area network (WBAN) or a body sensor network (BSN) or a medical body area network (MBAN), is a wireless network of wearable computing devices [32–34]. BAN devices may be embedded inside the body, implants, may be surface-mounted on the body in a fixed position Wearable technology or may be accompanied devices which humans can carry in different positions, in clothes pockets, by hand or in various bags. Whilst there is a trend towards the miniaturization of devices, in particular, networks consisting of several miniaturized body sensor units (BSUs) together with a single body central unit (BCU) [35]. Larger decimeter (tab and pad) sized smart devices, accompanied devices, still play an important role in acting as a data hub, data gateway and providing a user interface to view and manage BAN applications. The development of WBAN technology started from 1995 with the idea of using wireless personal area network (WPAN) technologies to implement communications on, near, and around the human body. About six years later, the term "BAN" came to refer to systems where communication is entirely within, on, and in the immediate proximity of a human body [36]. A WBAN system can use WPAN wireless technologies as gateways to reach longer ranges. Through gateway devices, it is possible to connect the wearable devices on the human body to the internet. This way, medical professionals can access patient data online using the internet independent of the patient location [36].

The IEEE 802.15.6 working group established the first draft of the communication standard of WBANs in April 2010, optimized for low-power on-body/in-body nodes for various medical and non-medical applications [37]. The approved version of the IEEE 802.15.6 standard was ratified in February 2012 [38]. The main issue addressed in this standard is the requirement of quality of service (QoS) with limitation of power in sensor nodes in WBANs. WBANs can be used for different applications, such as medical, entertainment, and military applications. In all cases, sensors are attached to the human body. The sensors should be small in size, consume low power, be energy efficient [4], and be comfortable to wear by humans in any situation.

The rapid development in nano-technologies over the last two decades promotes the manufacturing of nano-machines like nano-sensors, nano-actuators and nano-processors [1, 2, 11, 14, 39], which further facilitates the application of BANNs. The BANNs, a kind of the general Wireless Body Area Network (WBAN) architecture [4], can be defined as a collection of nano-machines attached on or implanted in human body which have the capability of communicating with each other. The BANNs are expected to be an appealing solution for many critical applications in the field of biomedicine, such as health monitoring, genetic engineering, immune system support and drug delivery systems [3–6].

1.1.2 BANNs Applications Fields

Ubiquitous healthcare is becoming a reality thanks to the advances in sensing and communication technologies, which make it possible to provide monitoring and diagnosis services outside the premises of healthcare providers. The Internet of Things (IoT) is the main paradigm through which medical devices will be connected to the Internet, thereby empowering near-real-time health services and transforming a pa-

Figure 1-3: Immune system support

tients physical space into a smart space. Recent developments in nanotechnology are giving rise to the Internet of Nano-Things, BANNs with a new set of fine-grained and highly sophisticated healthcare applications that can be run inside the human body. It has been successfully applied in healthcare, health monitoring, support immune systems, creating novel drug delivery systems, detecting the presence of infectious agents, and identifying specific types of cancer [10, 40].

(1) Immune System Support. The immune system (Fig. 1-3) is composed by several nano-machines that protect organism against diseases. These nano-machines are a collection of nano, micro and macro systems, including sensors and actuators, activating in a coordinated way to identify and control foreign and pathogen elements. Nano-machines can be used to help the detection and elimination procedures. They could realize tasks of localization and response to malicious agents and cells, such as cancer cells [41], resulting in a less aggressive and invasive treatments compared to the existing ones. Therapeutic applications involve the direct interaction with biological phenomena. Nanomachines can respond to commands instructing them

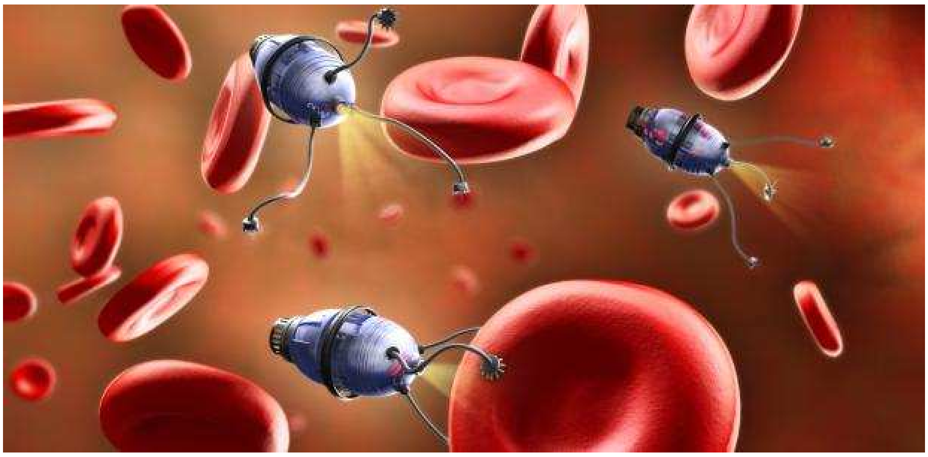

Figure 1-4: Nanorobot

to administer a certain drug, destroy tumors via tissue reengineering, or restore the glucose feedback loop of diabetics.

(2) Bio-hybrid Implants. These are aimed at supporting or replacing components such as organs, nervous tracks or lost tissues. Nanonetworks can provide friendly interfaces between the implant and the environment with nanorobot (Fig. 1-4). Restoration of central nervous system tracks is a possible application of bio-hybrid implants. The facile combination of polymer nanostructuring with biomolecule immobilization enables mechanically robust biohybrid components of interest for nanoscale biomedical, electronic, photonic, and robotic applications [42].

(3) Drug Delivery Systems. These are another specific type of implants. For instance, these systems could help to compensate metabolism diseases such as diabetes. In this sense, nano-sensors and smart glucose reservoirs or producers can work in a cooperative manner to support regulating mechanisms. Drug delivery systems (Fig. 1-5) could also help to mitigate the effects of neurodegenerative diseases by delivering neurotransmitters or specific drugs [43].

In targeted drug delivery, therapy on a target site (e.g., diseased cells or tumors) in a human body is performed by encapsulating drug molecules in drug delivery carriers, delivering the carriers to the target site, and releasing the drug molecules from the carriers at the target site. Targeted drug delivery therefore reduces the potential side effects of drug molecules on non-targeted sites [44]. Existing research on drug delivery

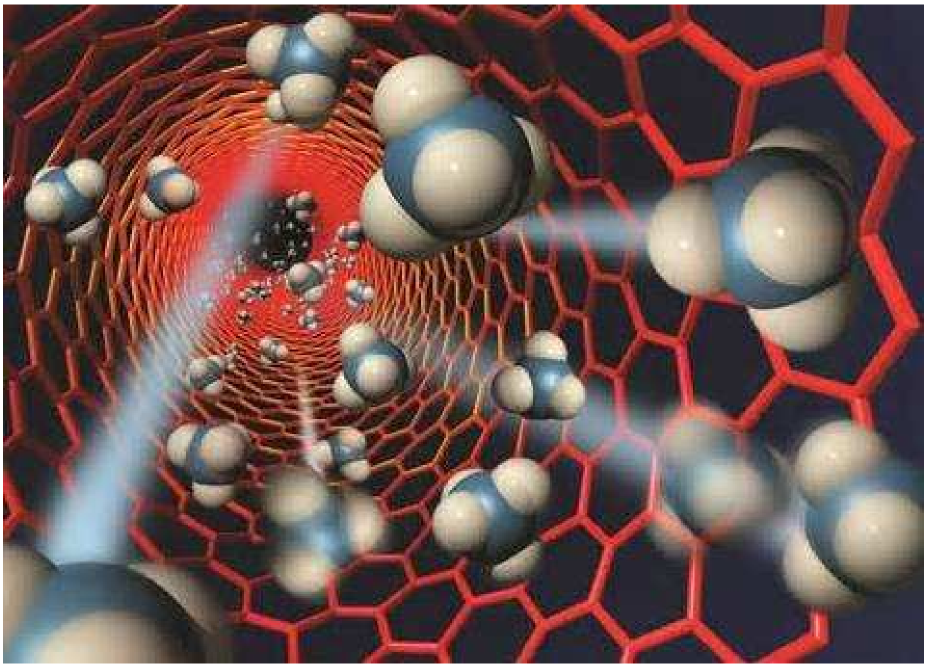

Figure 1-5: Drug delivery systems

develops drug delivery carriers that can be targeted to a specific site in a body (e.g., tumors), where the drug molecules are released in response to specific conditions such as temperature. Molecular communication may provide alternative techniques to improve the accuracy of targeting and efficacy of therapy through the coordination of bio-nano-machines (i.e., drug delivery carriers). For instance, bio-nano-machines that identify a target site may release molecules to recruit other bio-nano-machines in the environment toward the target site, thereby, the concentration of bio-nano-machines at the target site is increased. Also, a group of bio-nano-machines at the target site may communicate to determine the rate of drug release depending on the conditions (e.g., the number of bio-nano-machines at the target site) to achieve a sustained drug release.

In those scenarios, drug localization to targeted cells is achieved by encapsulating, entrapping or encapsidating drug and therapeutic molecules/particles or agents in nano-vectors. These nano-vectors are mainly conveyed to the targeted cells through the cardiovascular system, which ordinarily carries nutrients to all cells in the body. The most common nano-vectors are nano-carriers such as liposomes, micelles, den-

Figure 1-6: Health monitoring

drimers, nano-spheres, drug conjugates, viral nano-particles, inorganic nano-particles, DNA capsules and quantum dot [43]. These nano-vectors, which are basically bio-compatible and biodegradable, are often equipped with capabilities such as long circulation, internal/external stimuli responsiveness and targeting characteristics, to make them capable of transporting and delivering the drug molecules to the targeted sites. The zinc-based nano-motors [45] and the smallest medical robot [46] could one day lead to huge medical advancements. The ultimate goal of systems is to provide therapeutic, diagnostic, and monitoring tools for addressing medical challenges.

(4) Health Monitoring. Nano-sensors can be installed in a patients body to monitor the patients daily activities and alert healthcare providers and emergency units of abnormal changes in patient activity behavior (Fig. 1-6). In physiological signal monitoring or sensing (e.g. ECG monitoring), applications center mainly on the capturing periodical readings that reflect the status of a certain organ or tissue, or the level of a certain chemical or substance in the blood stream.

Oxygen and cholesterol level, hormonal disorders, and early diagnosis are some examples of possible applications that can take advantage of inbody nano-sensor networks [41]. The information retrieved by these systems must be accessible by relevant actors. Thus, nanonetworks must provide the proper level of connectivity

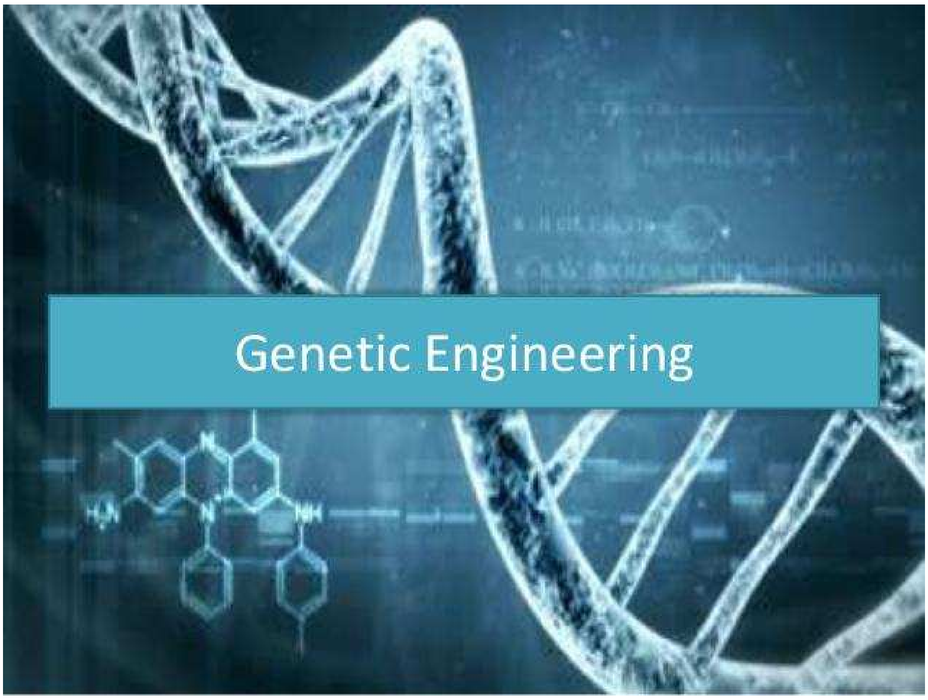

Figure 1-7: Genetic engineering

to deliver the sensed information. BANNs can also detect the presence of certain molecules, or viruses and send alerts. Detection can be more sophisticated and focus on abnormalities in the tissues or organs being monitored, such as indications of the onset of a heart attack. Applications that involve detection of viruses, or detection of certain abnormalities in the functioning of an organ or the composition of a tissue, usually require careful design of thresholds and flags that will trigger alerts.

(5) Genetic Engineering. Manipulation and modification of nano-structures such as molecular sequences and genes can be achieved by nano-machines. The use of nanonetworks will allow expanding the potential applications in genetic engineering (Fig. 1-7).

1.2 Motivations

Body Area Nanonetworks (BANNs) are an important class of emerging nanonetworks, where tiny nano-machines move in human body and can communicate with each other over peer-to-peer wireless link. Since they can provide inexpensive and continuous health monitor services, BANNs hold great promises for many important biomedical applications in immune and drug delivery systems. In these systems, it is critical for nano-machines to collect real-time data information. However, due to the constraint of extremely limited energy stored in nano-machines, posing a great obstacle to future these important applications. To efficiently support these applications with stringent energy requirements, it is of great importance to explore energy efficient data collection scheme in BANNs.

To the best of our knowledge, the concept of BANNs which specifies the general WBANs under the nano-scale began to emerge in the recent four years [6, 7, 10, 16, 18, 40], and the study on the design of energy-efficient operations for BANNs is largely uninvestigated. In particular, the data collection scheme, a key component of the energy consumption in BANNs, should be carefully addressed. Piro *et al.* [47] proposed an initial greedy scheme for collecting physiological data of human body, and it is expected that there still remains huge room for the improvement of data collection. Moreover, we notice that the path loss issue during the data collection process is usually neglected in previous studies, however, the path loss actually influences the energy consumption for a target nano-node transmitting data to its corresponding nano-router (since the path loss significantly impacts the quality of the collected data).

Motivated by these observations, this paper aims at taking a step forward in the design of energy-efficient data collection scheme under different scenarios for BANNs for prolonging the lifetime of the BANN as well as improving the data transmission quality. We first propose a lightweight data collection scheme under a simple yet efficient scenario with multiple nano-nodes and only one nano-router in BANNs. Then, we further propose a new energy efficient data collection scheme under a complex scenario with multiple nano-nodes and nano-routers in BANNs. Finally, we propose a relay-based energy-efficient data collection scheme with minimum energy coding. We also provide extensive simulations to validate our scheme.

The main contributions of this paper can be summarized as follows:

- We focus on the framework for supporting energy efficient data collection in

BANNs. The proposed framework consists of inside-body network and outside external healthcare monitoring system. Inside-body network (composed of nano-nodes, nano-routers, and a nano-interface) is connected to the outside external healthcare monitoring system using nano-interface.

- In the view of a simple scenario with only one nano-router and multiple nano-routers, a lightweight data collection scheme for BANNs is proposed. First, a sleep/wake-up mechanism is introduced to avoid the unnecessary energy consumption when no external request comes. Then, with a careful consideration of both node available energy and transmission energy consumption, we design a new node selection strategy to further reduce the energy consumption in the data collection process.

- Based on timing/priority mechanism, we further design an energy-efficient data collection scheme with multiple nano-routers in BANNs. For saving the unnecessary energy consumption, we categorize data as emergency data (ED) and normal data (ND). Then, we further use this classification for generating distinct packets and assigning priorities. Usually, the system transfers normal data (ND) regularly, and in case of emergency sends emergent data (ED) immediately.

- We also consider relay-based energy-efficient data collection scheme with minimum energy coding (MEC). Maximum nano-node density for reliable communication in BANNs is derived, and density dependent reliability analysis is conducted. Both Rate-energy and delay-energy tradeoffs are also investigated with achievable rates, with constant codebook size and constant Hamming distance, separately.

- We conduct network simulations for both the energy-efficient data collection scheme and the benchmark greedy scheme, to demonstrate the energy efficiency achieved by our proposed scheme as well as illustrate the impacts of network parameters on network performance.

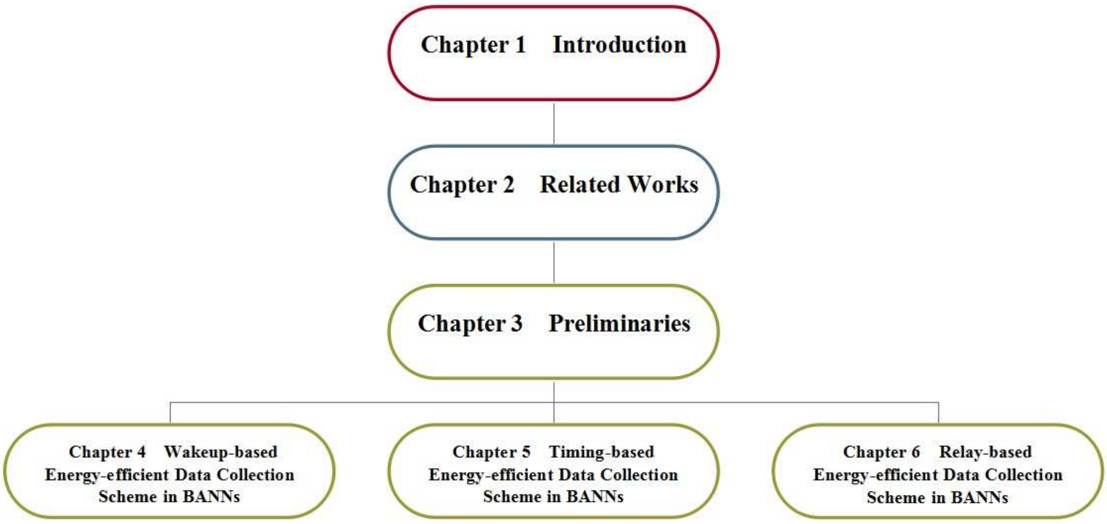

Figure 1-8: The main contents of this thesis

1.3 Thesis Outline

In this thesis, the overall aim is to provide a comprehensive study on energy efficiency data collection for Body Area Nanonetworks. The main contents of this thesis are summarized as follows (you can also see Fig. 1-8):

Chapter 2 Related Works. In this chapter, we introduce previous work related to wakeup-based, timing-based and relay-based energy-efficient data collection schemes in BANNs.

Chapter 3 Preliminaries. This chapter introduces frameworks for supporting energy efficient data collection in BANNs. The proposed architecture consists of inside-body network and outside external healthcare monitoring system. Inside-body network (composed of nano-nodes, nano-routers, and a nano-interface) is connected to the outside external healthcare monitoring system using nano-interface. This paper is concerned with how to collect data in different scenarios.

Chapter 4 Wakeup-based Energy-efficient Data Collection Scheme in BANNs. In this chapter, we consider a simple scenario with only one nano-router, propose a lightweight data collection scheme in BANNs. First, a sleep/wake-up mechanism is introduced to avoid the unnecessary energy consumption when no external request comes. Then, with a careful consideration of both node available energy and transmission energy consumption, we design a new node selection strategy to further reduce the energy consumption in the data collection process. Finally, we conduct extensive simulations for both the proposed data collection scheme and the benchmark greedy scheme to illustrate the energy efficiency of our scheme as well as to discuss the impacts of network parameters on network performance.

Chapter 5 Timing-based Energy-efficient Data Collection Scheme in BANNs. In this chapter, we further propose a new energy efficient data collection scheme under a complex scenario with multiple nano-nodes and nano-routers in BANNs. With the scheme, we first categorize data as emergency data and normal data to fully consider the limited energy constraints. We then use this classification to generate distinct packets and assign priorities. In BANNs, the normal data is usually sent regularly, while the emergent data is sent immediately. Extensive simulations are also provided to validate energy efficiency of our scheme in comparison with other benchmark greedy scheme, and to illustrate impacts of network parameters on network performance.

Chapter 6 Relay-based Energy-efficient Data Collection Scheme in BANNs. In this chapter, we propose a relay-based energy-efficient data collection scheme with minimum energy coding. Under the scheme, we derive maximum nano-node density for reliable communication in BANNs, and conduct density dependent reliability analysis. Both rate-energy and delay-energy tradeoffs are also investigated with constant codebook size and constant Hamming distance, respectively. We also provide extensive simulations to validate our scheme.

Chapter 7 Conclusion. This chapter concludes the thesis and discusses the interesting future research topics.

Chapter 2

Related Works

In this chapter, we present a survey of related works on the studies of timing-based, wakeup-based and relay-based energy-efficient data collection scheme in BANNs.

2.1 Wakeup-based Energy-efficient Data Collection

The BANNs are expected to be an appealing solution for many critical applications in the field of biomedicine, such as health monitoring, genetic engineering, immune system support and drug delivery systems [3–6]. To support the application and commercialization of BANNs, designing efficient operations for such networks is of great importance [17, 48–51].

It is worth noting that, however, the nano-machines in a BANN are limited in size (usually from $1nm$ to $100nm$), leading that the energy supplying devices are difficult to be utilized, and thus BANNs suffer from seriously limited energy constraint which has become a roadblock stunting their further development. As a result, the operations in a BANN should be carefully designed in an energy-efficient way such that we can extend the lifetime of the BANN as much as possible. By now, a number of research efforts have been devoted to the design of energy-efficient operations in the general WBANs. For instance, Okundu *et al.* [52] proposed a MAC protocol which applies the single-hop communication and centrally controlled wake-up/sleep times to reduce the energy consumption for WBANs. Following this line, the energy-efficient

MAC protocols were further explored for WBANs with the star network topology and the masterslave-based network topology in [53] and [54], respectively. In [55], Chi *et al.* constructed the prefix-free codes to minimize the transmission energy consumption with a guaranteed throughput for wireless nano-sensor networks. Magno *et al.* [56] discussed the methods of exploiting wake-up receivers and heterogeneous sensors in WSN applications to reduce the average power consumption of individual nodes. In [57], Casamassima *et al.* presented a power management strategy combining an ultra-low power wake up radio with context awareness in WBANs. The context aware power manager based on activity recognition decides which nodes must be activated exploiting a nano-power wake up radio and power management policies.

To the best of our knowledge, the concept of BANNs which specifies the general WBANs under the nano-scale began to emerge in the recent four years [6, 7, 10, 16, 18]. Thus the study on the design of energy-efficient operations for BANNs is largely uninvestigated. In particular, the data collection scheme, a key component of the energy consumption in BANNs, should be carefully addressed. Piro *et al.* [47] proposed an initial greedy scheme for collecting physiological data of human body, and it is expected that there still remains huge room for the improvement of data collection. Moreover, we notice that the path loss issue during the data collection process is usually neglected in previous studies, however, the path loss actually influences the energy consumption for a target nano-node transmitting data to its corresponding nano-router (since the path loss significantly impacts the quality of the collected data).

Thus, we aim at taking a step forward in the design of wakeup-based energy-efficient data collection scheme for BANNs. For such a BANN, we first apply a sleep/wake-up mechanism to activate the nano-nodes within a specific region of a nano-router when data request happens (the nano-nodes without the region keep the sleep state for saving energy). We then design the node selection strategy which utilizes the estimated remaining energy after the data collection process (rather than the available energy before the data collection process in [47]) as the metric to select the nano-node from which the data be collected, for prolonging the lifetime of the

BANN as well as improving the data transmission quality.

2.2 Timing-based Energy-efficient Data Collection

In recent years, little work has been done targeting BANNs. The major focus of these studies is to improve the physical and MAC layer. A few routing protocols for WNSNs have been proposed. However, due to diffusing nano-nodes inside the human body and delivering observed information timely makes those existing routing protocols not directly applicable for BANN. In the view of prior studies, a routing protocol that can conserve energy as well as decrease delay and packet loss is desirable for BANN.

Heuristic method aims to reduce heavy processing load on nano-nodes [58]. Initial timing acquisition in narrow-band IoT (NB-IoT) devices is done by detecting a periodically transmitted known sequence. In [59], the authors presented a hardware implementation of the maximum likelihood cross-correlation detection. In [60], the receiver design for timing modulated molecular communication system was studied. In order to reduce the complexity of the receiver, several simplified detection algorithms were studied, and an order statistic based detection method was proposed to simplify the receiver specially. Energy model for self-powered nano-sensors to jointly analyze the energy harvesting and energy process was proposed in [61]. Piezoelectric nano-generator was used for realization of energy harvesting mechanism and they were further reviewed for EM communication. A protocol stack for BANN was proposed in [40], and an energy-harvesting aware MAC protocol perform neighbor discovery for finding active and idle nodes. At the network layer, two different routing protocols are introduced for minimum energy conservation namely optimal-energy aware routing protocol and greedy-energy aware routing protocol. In optimal-energy aware routing protocol, the router is aware of the remaining energy in its cluster. Whereas, in the greedy-energy aware routing protocol, request is forwarded to the node with the highest energy.

Selective flooding routing is proposed in [47] that limits the direction of flooding in order to save bandwidth. The basic principle of this approach is to reduce transmission of same packet. In order to address this issue, whenever a packet is received it is forwarded in the opposite direction. However, if a node has already received the packet, then it was not retransmitted.

In the light of existing work, we can conclude that in order to meet the requirements of BANN, energy efficient protocols are required for satisfying the needs of healthcare monitoring applications. Hence, based on limited energy constraints, we categorize the data as emergency data (ED) and normal data (ND). We further use this classification for generating distinct packets and assigning priorities. Emergency packet (EP) carries the most crucial information and needs to be delivered to the external healthcare monitoring system with minimum delay, while regular packet (RP) is responsible for delivering routine information. Since EP contains critical information, therefore, they have the highest priority. Whereas, RP is taken as low priority packet. For the sake of collecting ED and ND, during each interval T_x, a number of participating nodes are nominated. The purpose of participating nodes is to minimize energy consumption for data reporting as well as data aggregation.

According to [8], a mechanism is required to handle important data delivery to the outside system. However, in all the previous work, outside system is continuously updated irrespective of data importance and when request rate is increased important data delivery can be affected. In order to handle these issues a routing protocol is required that gives more priority to the delivery of important information.

In the view of the aforementioned problems, a lightweight and scalable BANN architecture is proposed. The proposed architecture consists of Inside-body network and outside external healthcare monitoring system. Inside-body network (composed of nano-nodes, nano-router, and a nano-interface) is connected to the outside external healthcare monitoring system using nano-interface. In this study, we have proposed time-based energy efficient data collection scheme (TBEES), composed of MAC and routing algorithm. At the routing layer, priority-based routing algorithm is used, where nano-routers are responsible for periodic inquiry of the body parameter and sending this information to the external healthcare monitoring system. In order to save energy, in one interval only selected participating nodes can take part in request/response process. All entities (nano-nodes and nano-router) are aware of the information they are transmitting and the data transmission is done based on its priority. Whereas, at the MAC layer a special priority queue is maintained, the purpose of the priority queue is to distinguish priority packets and entertain them accordingly.

2.3 Relay-based Energy-efficient Data Collection

During the past few years studies on body-centric communication have been gradually increasing [62]. Due to the evolution of novel materials like graphene [63], it is possible to perform communication operating at THz frequencies, and the interest in these frequencies for communication of nano-devices either on-side or in-side the human body is growing as well. In [64], a novel channel model inside the body at THz frequencies for communication between these nano-devices based on extensive numerical and measurement studies have been presented, while considering various parameters like distance, number of sweat ducts and frequency.

Ad hoc nanonetwork is a group of wireless nano-devices, which are communicating with each other without relying on any infrastructure [65]. It is a decentralized and self-organized infrastructureless wireless nanonetwork, and data are delivered to destination directly by using either one-hop path or multihop path through multiple intermediary nodes. Therefore, it is also called as multi-hop wireless networks. They are flexible and can be effectively deployed in many applications such as Wireless Personal Area Networks (WPANs) , Body Area Nanoetworks (BANNs), Health Care Monitoring etc [36].

In multi-hop wireless networks, nodes are operating with limited battery resources and it is not likely easy to replace them in some situations. Thus, topology control algorithm must be energy efficient to prolong network lifetime while satisfying network performances. There are many topology control algorithms proposed in decades, and they can be broadly divided into two main categories based on their power conservation techniques i.e. State Scheduling and Transmission Power Control techniques.

The first work on relay-based nanonetworks is presented in [66]. The authors investigated the challenges to be addressed the realization of relay-based nanonetworks. In [67], the authors showed that without any medium access control mechanism, low weight channel codes can be used for communication in nanonetworks, together with OOK modulation, without considering any specific coding scheme. To address the severe energy efficiency requirement, we proposed novel minimum energy channel codes (MEC) for reliable nano-scale communications in [68]. K. Chi *et al.* [55] formulated an integer nonlinear programming problem to construct prefixfree codes with minimum ACW under the constraint of average codeword length (ACL) to minimize the transmission energy consumption while guaranteeing the throughput requirement. To reduce the area of the candidate node in multi-hop directions minimizes energy consumption. A link cost function is used for selecting the next hop which is is based on the energy consumption, capacity, and distance. All nodes that have low-cost function win a chance to be selected as the next hop [69]. Low energy consumption mechanism for routing is investigated in [70] to select next-hop nano-nodes on the basis of their energy and available load optimizes harvested energy consumption, and the Markov decision process is used for efficiently utilizing the harvested energy for nano-nodes in WNSN.

We have considered a nano-sensor network, in which time or frequency resources are orthogonally allocated, and investigated its feasibility. However, nanonetworks with central controller units might not always be feasible. Therefore, investigation of relay-based nanonetworks is an open research problem requiring further investigation. To the best of our knowledge, no channel coding scheme which can guarantee reliability has been proposed for relay-based nanonetworks.

Thus, we propose using MEC for reliable communication in relay-based nanonetworks. A probabilistic analysis is conducted to show that the reliable communication is possible in relay-based nanonetworks without any medium access scheme. We investigate the maximum node density that allows perfectly reliable communication by increasing the code distance. Relation between nano-node density of relay-based network and reliability is revealed through simulations. We also investigate rate-delay-energy tradeoffs of relay-based nanonetworks with MEC. It is shown that, for maximally dense networks, increasing delay using larger source set cardinality increases the rate. Achievable rates for sufficiently large code distance and source set cardinality are also analytically derived.

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Chapter 3

Preliminaries

For supporting energy efficient data collection in BANNs, this chapter introduces frameworks, including inside-body network and outside external healthcare monitoring system. Inside-body network (composed of nano-nodes, nano-routers, and a nano-interface) is connected to the outside external healthcare monitoring system using nano-interface.

3.1 Architecture in BANNs

System architecture is composed of an in-body network and an external healthcare monitoring system. In-body network communicates with the external healthcare monitoring system via nano-interface. Whereas, communication between nano-interface and the external healthcare monitoring system is provided using a wireless/wired broad band technology. In BANN, nano-nodes are deployed for tracking biological parameters for the sake of remote health monitoring. These nano-devices are capable of exchanging this information among them and with the nano-router. While nano-router is responsible for delivering this information to external healthcare monitoring system using nano-interface. Nano-router keeps the external healthcare monitoring system updated by generating periodic requests for observing different body parameters. In response to the request messages, nano-nodes reply with answer messages. After receiving periodic answer messages, nano-router delivers collected information

Figure 3-1: BANN architecture

to the external healthcare monitoring system. Moreover, the external request is generated when nano-router fails to send its scheduled report or external healthcare monitoring system needs some urgent information.

A common BANN is shown in Fig. 3-1, where different nano-sensors are deployed inside the human body for collecting different parameters. Nano-sensors are capable of exchanging observed information among them and transmitting this information to the external healthcare monitoring system using nano-interface. Nano-interface is connecting the In-body network to the external healthcare monitoring system through Internet.

Star and star-mesh hybrid topologies show promise for meeting wearability, size, and data-fusion needs. Both the star and star-mesh hybrid topologies exploit the resource asymmetry (aggregator versus node) and hierarchical nature of BANN. In a star network, all peripheral nodes connect to the body aggregator, which allows for high data throughput and simplified routing. Having a central coordinator also means having a single point of failure, however. To address that weakness, a star-mesh hybrid topology extends the traditional star approach and creates mesh networking among central coordinators in multiple star networks. The failure of a single coordinator can trigger the reorganization of nodes and coordinators with minimal service interruption. Star-mesh hybrid topologies could also link aggregators and bridge networks from the body area to a wider area[11].

Data processing at the sensor node reveals information specific to the sensor's locality. Information, however, might also come from relationships between data collected at multiple sensors over time. The body area aggregator has the important role of combining data from multiple sensors on the body. The aggregator typically possesses a richer collection of resources and a greater energy capacity than the BANN nodes. In addition to its role as a data fusion center, the aggregator creates a bridge between the nodes and higherlevel infrastructure. It can also offer user interfacing and can possess its own sensing capabilities. The convergence of wireless technologies, such as Bluetooth, cellular, and IEEE 802.11; interactive user interfaces such as touch screens; and highly capable embedded microprocessors, such as the ARM 11 and OMAP, make newer mobile phones and personal digital assistants attractive hosts for body area aggregation.

At the body aggregator, data processing must reveal relationships among the body's sensors. With progressively richer resources, more sophisticated and dedicated datamining systems could uncover information related to small and large populations. Each successive hierarchical level must aggregate more data by supporting higher data rates, making more general inferences, and archiving more information. Consequently, hardware and software is needed to interoperate through multiple levels of infrastructure to share information. Moreover, information gained at each level will provide feedback to and inform the refinement of classification schemes, feature-detection algorithms, and sensor coordination, placement, and design.

3.2 Nano-node Energy Consumption

As previously mentioned, the limited nano-device energy resources lead to the use of a hierarchical nanonetwork architecture to enable the junction between macro and nano worlds, following the scheme described in [14]. As shown in Fig. 3-1, nano-nodes

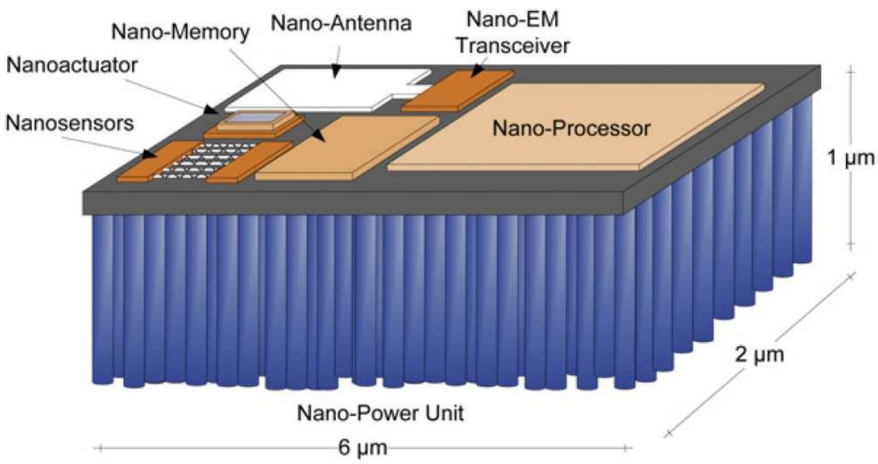

Figure 3-2: Architecture of a nano-sensor device

are the smallest nano-devices (with just a few *um* in size) in our scenario and belong to the lowest level of the hierarchy, traveling through the veins. In the upper level, the nano-router gathers the data collected by nano-nodes and is able to communicate with the gateway using a THz communication system. The gateway dispatches sensor data to a traditional external system via WiFi or Bluetooth (the communication between the gateway and the nano-router is not covered in this work). It is noteworthy that a critical aspect of properly designing the communication scheme is to determine the consumption of each nano-device. Thus, in this section, we estimate their energy consumption based on feasible technologies in order to design a communication schedule able to work under realistic conditions.

The energy required by a nano-node to communicate with a nano-router should be accurately determined to accomplish a specific application, since the operating environment conditions change according to the scenario under study (varying the amount of harvested energy). To address this problem, we refer to a previous work [71], in which the nano-device proposed is in the lowest level of the nanonetwork hierarchy (nano-node). A nano-node must gather, store and process sensor information to later transmit it via a THz band communication system. These tasks should be carried out under an appropriate energy consumption scheme resulting in an acceptable recharge time for nano-devices. In this proposal, the nano-device is divided into five main components [14] (see Fig. 3-2), namely: nano-processor, memory nano-modules (RAM and ROM memories), graphene radiocommunication nano-system, nano-sensor, and energy nano-generator. In order to encompass all these components in a tiny device, the dimensions of the nano-node proposed in [72] are $8 * 8 * 3um$. In the following subsections, the four components are reviewed, paying special attention to power consumption, while the energy required for the nano-generator is further analyzed in next section.

- **Nano-processor**: The nano-processor is responsible for handling the basic protocol instructions received from the nano-router, such as waking up/sleeping, reading data from the sensor or transmitting a frame, among others. Moreover, it will drive the operation of the remaining nano-node components to bring out the best performance of the nano-device and ensure its proper functioning in terms of sensor data collection, storage, processing and communication. However, carrying out these functions is not an easy task, due to the fact that the available area in the nano-node is tightly restricted, and therefore, the resources available to the nano-processor will also be rather limited. This concern was extensively discussed and analyzed in [71], concluding that the SiGe-based transistor (with 7 nm technology) is the best technological option nowadays to obtain a functional nano-processor that satisfies the expected nano-node requirements in both size and energy consumption. Specifically, its power consumption, as analyzed, is estimated to be 140 nW for a processor working at 500 kHz. This operating frequency is enough to accomplish the aforementioned required tasks while maintaining the condition of very low energy consumption.

- **Memory nano-modules**: Diverse types of memories are encompassed in the nano-node; each one of them intended to store information according to different purposes. Firstly, to read/write data rapidly, a RAM (Random Access Memory) module is included. Since the physical position of the data to be read or written is irrelevant, it makes RAM an appropriate solution for cache memories, where data handled by the processor will be temporarily stored. Analyzing the complete RAM family, the technological solution that best fits our particular needs is the A-RAM memory, which combines the advantages of dynamic (DRAM) and static (SRAM) memories [73]. However, due to its volatile nature, A-RAM requires a continuous refreshing signal to retain the data. Secondly, to store permanent data, such as the preset software to boot the nano-device, a ROM module is also required. For this purpose, NOR flash memory is the best choice, since it assures low read access times, preserving an acceptable bit density and restrained energy consumption when reading. Regarding their power consumption, as reported in [71], the consumption of RAM and ROM modules is included in the value given for the nano-processor.

- **Nano-sensor**: Nano-sensors are extremely small integrated devices engineered from nanomaterials or biological materials. New physical, chemical, and biological nano-sensors have been developed by employing graphene and other nano-materials in their fabrication process [74], which contribute novel properties different than the well-known traditional materials. They are used to detect and respond to a physical property from the environment. Nano-sensors work the same way as conventional sensors, but their size is extremely small billionths of a meter. They can perform set of simple functions to manipulate signals for detecting, modifying and recording measurements. Nano-sensors come in a variety of sizes and shapes ranging from the size of a macromolecule to that of a bio-cell. In biomedical applications, the size of the nano-sensors used for taking invasive measurements is extremely small compared to the one used to record noninvasive measurements. The application area, measurement site, the end goal, and safety constraints play a critical role in deciding the material and size of a nano-sensor.

  In healthcare domain, nano-sensors can be used for different purposes including monitoring, detection, and treatment. For example, nano-sensors can detect chemical compounds in concentrations as low as one part per billion, or the presence of different infectious agents such as virus or harmful bacteria. An ex-

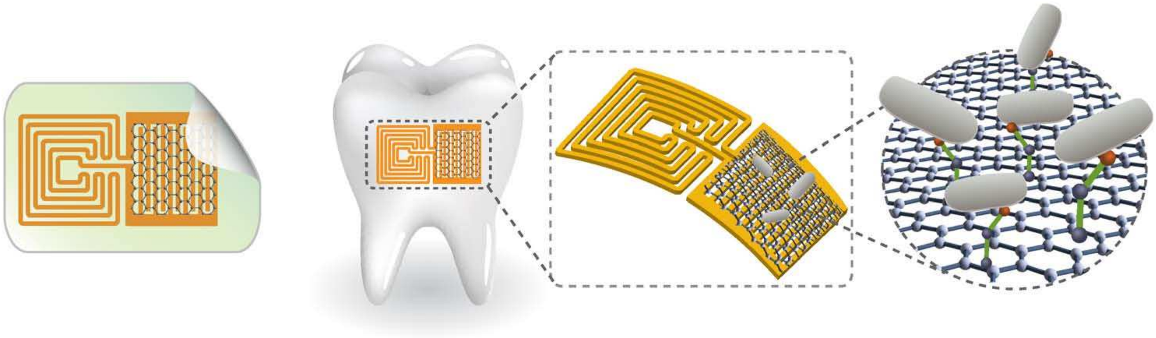

Figure 3-3: Biotransferrable graphene wireless nano-sensor

ample of such a nano-sensor is bio-transferrable graphene wireless nano-sensor [75] illustrated in Fig. 3-3. The proposed architecture of bio-transferrable nano-sensor has a satisfactory response in sensing extremely sensitive chemicals and biological compounds up to single bacterium. It also has wireless remote powering and readout functionality.

3.3 Energy Harvesting Systems

At the nano-scale, traditional operations like the recharging or replacement of a battery are unfeasible, which leads us to look for new ways to appropriately power the nano-device components. Nano-generators are the most widely accepted technological solution by the scientific community [47, 61], and in particular, those fabricated using Zinc Oxide (ZnO) nano-wires. ZnO nano-wires are one of the most promising systems for energy harvesting [76], since they are able to convert mechanical strains and vibrations into electric energy due to their piezoelectric properties. To this end, nano-wires are vertically arranged and firmly fixed at one end to a substrate while the other end is free, thus allowing them to bend. Under this scenario, a voltage and current are induced and collected by both electrodes (the ends of the nano-wire). Once the voltage is adjusted (since the potential difference has an opposite sign depending on the nano-wire movement), the energy produced is stored in a nano-capacitor to later be employed in the feeding of the nano-device components.

In light of the network structure described in the introduction, the nano-router will only be fed by ultrasound waves, while the nano-nodes will be powered through their movement in blood flow, except for those in the acting range of ultrasounds. Thus, two different harvesting cases are studied: energy harvesting from blood flow, and energy obtained from an external source through ultrasound waves.

3.3.1 Energy Harvesting from the Bloodstream

In the scenario considered in our work, nano-nodes are deployed into the blood flow of a human body to form a nanonetwork. This working environment acts on a regular basis; the strain intensity depends on the blood pressure and the frequency of the heartbeat. Under these regular conditions, the average power density produced by a ZnO nano-generator reaches a value of 0.01 pW/um^3 with a peak voltage of 0.7 V [76]. This value was obtained under laboratory conditions when a regular strain at a frequency of 0.3 Hz was applied. In our work, the heartbeat has a minimum frequency of 1 Hz which would triple the average power produced. However, we assume the worst case as the energy harvested depends on different factors that require more exhaustive study, such as the position of the nano-device in the vein, blood pressure or the distance to the heart. Thus, adopting the nano-node dimensions suggested in [71], the nano-generator volume is 128 um^3 , so the envisioned average power produced by each nano-node when they are excited just by blood flow movement is 1.28 pW.

3.3.2 Energy Harvesting from an External Source

Concerning our proposal, the nano-router is only powered by an external source through ultrasounds. This technological solution resolves two main concerns. Firstly, the nano-router is placed in the epidermis tissue which tightly restricts their movement, and therefore, restricts their energy harvesting capacity as well. Secondly, the nano-router requires more energy than nano-nodes to do the task, since the nano-router components are larger in size and clearly more powerful and a high amount of energy to feed their components is needed, and their operating periods are longer than those for the nano-nodes.

In order to accurately estimate the power generated by ultra- sounds, we follow the methodology proposed in [77] since it fits our case study. As a starting point, we set the ultrasound intensity transmitted by the external source, which is restricted to a maximum of 720 mW/cm^2 by medical recommendations. Thus, we consider this value in order to maximize the energy harvesting. As the ultrasound signal must propagate through different biological tissues to reach nano-devices, the attenuation experienced must be taken into account. In particular, two different physical phenomena should be accounted for: the absorption of energy caused by the tissues, which is converted into thermal energy, and the reflection when the tissue changes.

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Chapter 4

Wakeup-based Energy-efficient Data Collection Scheme in BANNs

In this chapter, we consider a simple scenario with only one nano-router, and propose a lightweight wakeup-based data collection scheme in BANNs. First, a sleep/wake-up mechanism is introduced to avoid the unnecessary energy consumption when no external request comes. Then, with a careful consideration of both node available energy and transmission energy consumption, we design a new node selection strategy to further reduce the energy consumption in the data collection process. Finally, we conduct extensive simulations for both the proposed data collection scheme and the benchmark greedy scheme to illustrate the energy efficiency of our scheme as well as to discuss the impacts of network parameters on network performance.

4.1 System Model

The system consists of one nano-interface, one nano-routers and multiple nano-nodes. Nano-nodes collect data and transmit the collected data to the nano-router. After receiving data, nano-router transmits to nano-interface. The nano-interface is in a fixed position, whereas all nano-nodes move at a constant speed along the artery following the direction of the blood release. Further, in order to save the energy, the nano-interface and the nano-router are integrated together.

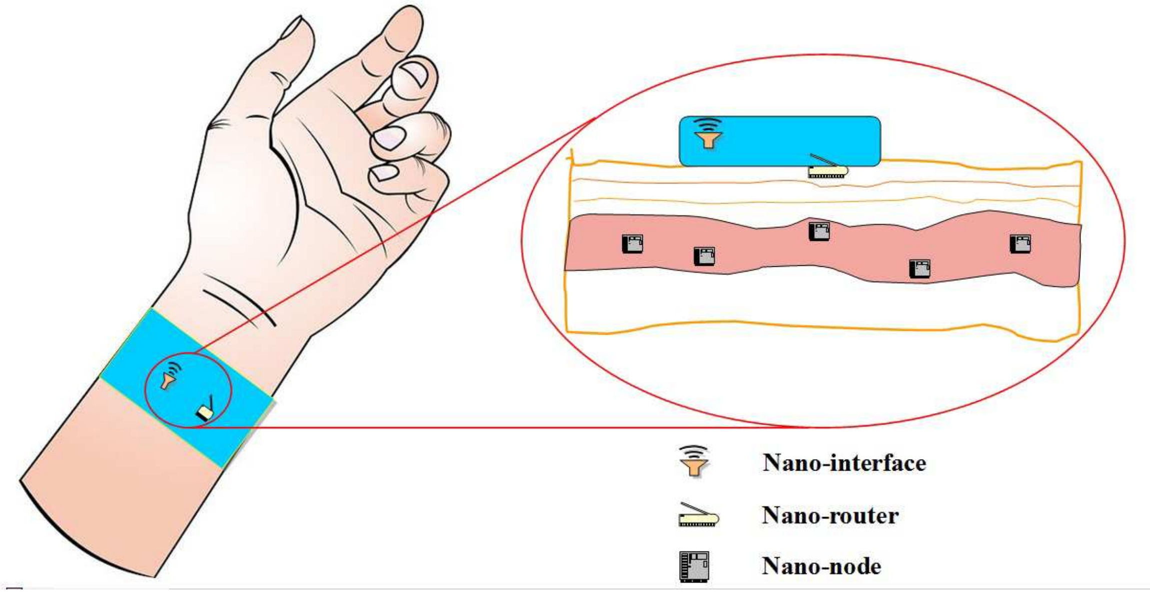


Figure 4-1: The system model consists of one nano-interface, one nano-routers and multiple nano-nodes.

The scenario under study is illustrated in Fig. 4-1 where an external portable device (nano-interface) is placed at the wrist of a hand, and feeds the nano-router by ultrasounds. The nano-router is implanted into the skin to be able to communicate with the nano-nodes, which are in constant movement in the bloodstream. Thus, to estimate the path loss between the nano-node and nano-router, the biological composition of the wrist of the hand has been modeled as a layered structure, similar to the model proposed in previous works [62, 78]. The upper layer is composed of skin, split into dermis and epidermis. Both human tissues have very similar electrical properties, as demonstrated in [79], thus, in our study, we have considered both as one single tissue. The middle layer represents the subcutaneous fat, which in the back of the hand is rather thin. This thinness makes this part of the human body one of the most suitable for establishing a BANN, since the distance between the outside of the human body and the vein is fairly short. Finally, the lower layer, which models the vein, is made up of blood. This will recreate the situation in which the nano-node is operating in the circulatory system. Both nano-devices must be encapsulated in a biocompatible capsule/artificial cell to be implanted into the human body, as cited in [77].

In our scenario, both nano-router and nano-node are supposed to be placed inside the human body. The nano-router is located in the skin, since its thickness allows a straightforward implantation. In our model, it is in the interface between the dermis and epidermis, facing downwards to keep its nano-antenna radiating to the vein and thus facilitating communication with the nano-nodes. The nano-nodes flow through a vein, and to study the more common scenario, we consider in our model that the nano-node is positioned in the center of the vein.

We assume that all nano-nodes adopt energy-harvesting techniques to continuously gain extra energy supply. Despite the continuous energy supply, operations of nano-nodes (e.g., sensing, receiving request and sending data) will consume their energy. The amount of consumed energy and harvested energy of nano-nodes will be introduced in Section 4.3 in detail. According to the amount of available energy, each nano-node can alternate on three states, namely, sleep state, active state and invalid state as follows:

- Sleep state: the nano-node keeps sleeping and will not do any operations on this state.

- Active state: when a request from a nano-router arrives at the nano-node, it will turn into active state from sleep state to perform the related tasks. After completing the task, it will automatically turn back to the sleep state.

- Invalid state: when the energy level of the nano-node falls below some threshold E_{th}, it will become invalid and cannot participate in any operation until its energy exceeds E_{th} again through the energy harvesting. The value of E_{th} will be given in Section 4.3.

It should be pointed out that energy consumption only happens when a nano-node is on the active state, while energy can be harvested no matter which state the nano-node is on. We assume that when there is no data request from the nano-router, all the nano-nodes prefer to stay on the sleep state to save energy.

The main notations of this chapter are summarized in Table 4.1

Table 4.1: Main notations

Symbol	Definition
M_r	size of request message
M_a	size of the activation messag
M_e	size of the energy feedback message
M_s	size of the answer message
E_{btx}	energy required to transmit a pulse
E_{brx}	energy required to receive a pulse
$E_{tx}(x)$	energy required to transmit a packet of x bits
$E_{rx}(x)$	energy required to receive a packet of x bits
E_{fb}	energy consumed for a nano-node transmitting the feedback message
E_{ans}	energy consumed for a nano-node transmitting the answer message
E_{full}	fully charged energy for nano-node
E_{th}	energy threshold
E_a	available energy for a nano-node
V_{cap}	total capacitance of the ultra nano-capacitor
n_c	number of compress-release cycles
V_g	generator voltage
ΔQ	harvested charge per cycle
A_s	spreading loss
A_{abs}	molecular absorption loss
$K(f)$	absorption coefficient
K_B	Boltzmann constant
T_0	reference temperature
L	length of the rectangular area
W	width of the rectangular area
l	length of wake-up region
d	distance between nano-node and nano-router
α	energy consumption exponent
λ	arrival rate of the external requests to the nano-interface
f	frequency of the electromagnetic waves
μ	density of nano-nodes

4.2 Wakeup-based Energy-efficient Data Collection Scheme

In this section, we elaborate the details of designing the energy-efficient data collection scheme, which consists of the hierarchical collection processes from nano-nodes to nano-router and from nano-router to nano-interface. Compared with the previous study [47], since we consider the more practical BANN scenario with the transmission path loss, the proposed scheme is specially designed with a sleep/wake-up mechanism, as well as a new nano-node selection strategy that selects the node with the maximal remaining energy after it executing the data sensing and transmission operations, rather than the node with the maximal current available energy before the data collection process, for improving the energy efficiency.

4.2.1 Basic Definitions

In order to state the data collection scheme clearly, we first define the following messages:

- Request message: the *request message* is used to indicate what kind of data the external entity is requesting. We use M_r to denote the size of a request message.

- Activation message: the *activation message* is used to change the state of a nano-node from the sleep state to the active state. We use M_a to denote the size of a activation message.

- Feedback message: the *feedback message* is used to indicate the location and the available energy level of a nano-node. We use M_e to denote the size of a feedback message.

- Answer message: the *answer message* is used to contain the information which is requested by the external entity (e.g., the presence of glucose in blood, cholesterol, and infectious agents). We use M_s to denote the size of a answer message.

4.2.2 Wake-up/Sleep Mechanism

As mentioned before, in our energy-efficient data collection scheme, we first introduce a sleep/wake-up mechanism for saving the unnecessary energy consumption. Notice that the nano-nodes do not execute any operation when there is no external request, thus the mechanism makes all the nano-nodes in a BANN keep on sleep state during this period (the nano-nodes under the greedy scheme [47] are always on the active state), which will greatly improve the energy efficiency of a BANN, especially in the case of small external request rate.

Once the the nano-interface receives a request message from the external entity, it forwards this message to the nano-router. Then, the nano-router broadcasts an activation message to the nano-nodes in a rectangle region centered at itself with length l and width W, i.e., the dashed area around the nano-router. We call this region the wake-up region hereafter. Since we consider a BANN distributed along the vein of a wrist, of which the width is quite small, in the sleep/wake-up mechanism we let the wake-up region only varies in length. This activation message is to activate all the available nano-nodes (the nano-nodes which are not on the invalid state) in the wake-up region and ask them to return the feedback message to their corresponding nano-router, while the nano-nodes outside this region cannot receive the activation message and still remain on the sleep state.

It is worth noting that the sleep/wake-up mechanism actually reduces the set of feasible nano-nodes which could be selected as the target node for data sensing and transmission. Except for saving the energy consumption of nano-nodes outside the wake-up region returning feedback messages, this mechanism also naturally reduces the energy consumption for data collection from a target nano-node to its corresponding nano-router. This is because that the expected distance between a target nano-node and its nano-router with the sleep/wake-up mechanism is shorter than that without the mechanism, and the energy consumption of data transmission is positive correlated with the transmission distance due to the path loss.

4.2.3 Nano-node Selection Strategy

By executing the sleep/wake-up mechanism, the nano-router can collect the feedback messages from all available nano-nodes in its wake-up region. Based on these feedback messages, the nano-router then applies the nano-node selection strategy to decide which nano-node should be selected as the target node for sensing and transmitting the required data.

With the greedy scheme in previous work [47], the nano-router will select the nano-node with the maximal available energy as the target node. However, under the practical BANN scenario with the transmission path loss, the greedy scheme is not applicable because that the nano-node with the maximal available energy could be very far away from the nano-router and this will cause huge energy consumption for data transmission. In order to improve the energy efficiency of the data collection scheme, we carefully design the nano-node selection strategy based on the combination of following two considerations: the current available energy of a nano-node, and the estimated energy consumption for this node transmitting the required data.

It is worth noting that the feedback message in our data collection scheme is well designed, which enables the nano-router directly obtain the current available energy level of each possible nano-node, as well as estimate the energy consumption for each nano-node transmitting the required data according to the corresponding location information (the estimation of energy consumption will be presented in Section 4.3. Then our nano-node selection strategy utilizes the estimated remaining energy after the data collection process as the metric (i.e., the difference between the current available energy and the estimated energy consumption), to select the nano-node with the maximal value of the metric as the target nano-node for executing further operations.

4.2.4 Operations of Data Collection Scheme

Based on the sleep/wake-up mechanism and the nano-node selection strategy, we can establish the complete energy-efficient data collection scheme for a BANN with the transmission path loss and a hierarchical network architecture which consists of nano-interfaces, nano-router and nano-nodes. The energy-efficient data collection scheme will be triggered after a request from the external entity arriving at the nano-interface. Then, the operations of the scheme can be summarized in Algorithm 1.

Algorithm 1 Energy-efficient Data Collection Scheme

The nano-interface sends the ***request message*** to the nano-router to indicate what kind of data the external entity is requesting.
The nano-router broadcasts an ***activation message*** to the nano-nodes in its wake-up region.
for each nano-node in the wake-up region **do**
    if the nano-node is not on the invalid state **then**
        This nano-node turns into the active state and return the ***feedback message*** to the nano-router.
    else
        The nano-node keeps the invalid state.
    end if
end for
The nano-router applies the **nano-node selection strategy** to select the target nano-node.
The nano-router sends the ***request message*** to the target nano-node.
The target nano-node collects the requested data from its surrounding.
The target nano-node returns the ***answer message*** to the nano-router.
The nano-router forwards the ***answer message*** to the nano-interface.
The nano-interface returns the ***answer messages*** to the external entity for further use.

4.3 Performance Evaluation

In this section, we conduct theoretical performance evaluation for the proposed data collection scheme in terms of its average available energy in each nano-node and average path loss of each data collection process. The average available energy is used to measure the energy consumption of the BANN and the average path loss is used to measure the quality (reliability) of the collected data.

4.3.1 Average Available Energy

We let E_{btx}, E_{brx}, $E_{tx}(x)$, and $E_{rx}(x)$ denote the energy required to transmit a pulse, receive a pulse, transmit a packet of x bits, and receive a packet of x bits to a unit distance of $1mm$, respectively. We adopt the Time Spread On-Off Keying (TS-OOK) modulation scheme, where in transmitting a message the presence of a pulse for a specific duration represents a bit 1 while the absence represents a bit 0 [80]. With the TS-OOK modulation, the probability that a collision occurs between femtosecond-long pulses is very low. Due to the fact that the time interval between transmissions is much longer than the pulse duration, several nano-nodes can concurrently use the channel without affecting each other. As in [80], the TS-OOK modulation is configured with the pulse duration, pulse time inter-arrival, and transmission range equal to $100fs$, $100ps$, and $10mm$, respectively. It is worth noting that the transmitter will consume its energy only when it transmits a pulse (i.e., bit 1), while the receiver should consume its energy whenever it receives a bit 1 or bit 0. Thus, the energy required to transmit a message of x bits can be written as:

$$E_{tx}(x) = x \cdot \beta \cdot E_{btx}, \tag{4.1}$$

and the energy required to receive a message of x bits can be written as:

$$E_{rx}(x) = x \cdot E_{brx} = 0.1 \cdot x \cdot E_{btx}, \tag{4.2}$$

where β is the probability that the bit 1 occurs (generally, β is set as 0.5 because symbols are equiprobable).

We let E_{fb} and E_{ans} denote the amount of energy consumption of a nano-node transmitting the feedback message, and the amount of energy consumption of a nano-node transmitting the answer message, respectively. Then according to [13], we have

$$E_{fb} = E_{rx}(M_a) + E_{tx}(M_e) \cdot d^{\alpha}, \tag{4.3}$$

$$E_{ans} = E_{rx}(M_r) + E_{tx}(M_s) \cdot d^{\alpha}, \tag{4.4}$$

where M_a, M_e, M_r and M_s denote the size (in bits) of activation message, feedback message, request message and answer message, respectively, d is the distance between the nano-node and the corresponding nano-router, and α is the energy consumption exponent.

The energy threshold E_{th} is defined as the amount of energy required to complete the request/response mechanism (below which the nano-nodes become invalid). Then E_{th} is determined as

$$E_{th} = E_{fb} + E_{ans}. \tag{4.5}$$

Regarding the energy harvesting of nano-nodes, the conventional mechanisms, e.g., solar energy and wind power, are not feasible in the nano-scale due to the technology limitations [61]. A pioneering mechanism to power nano-sensor motes is to harvest vibrational energy by exploiting the piezoelectric effect of ZnO nano-wires [81]. A piezoelectric nano-generator is consisted of an array of ZnO nano-wires, a rectifying circuit, and a ultra-nano-capacitor. When the nano-wires are bent or compressed, an electric current is generated between the ends of the nano-wires. This current is used to charge the capacitor. When the nano-wires are released, an electric current in the opposite direction is generated and used to charge the capacitor after proper rectification. The compress-release cycles of the nano-wires are created by an external energy source, such as air conditioning, heartbeat, etc. Since we focus on a BANN, we assume that the heartbeat represents the only energy source.

In [61], an analytical model for piezoelectric nano-generators has been already developed. The voltage V_{cap} of the charging capacitor can be computed as a function of the number of compress-release cycles n_c as follows:

$$V_{cap}(n_c) = V_g \left(1 - exp\left(-\frac{n_c \Delta Q}{V_g C_{cap}}\right)\right), \tag{4.6}$$

where C_{cap} is the total capacitance of the ultra-nano-capacitor, V_g is the generator voltage and ΔQ is the harvested charge per cycle, which is determined by the nano-wire array. Considering the technological constraints of nano-machines, typical values of such quantities are determined as $C_{cap} = 9nF$, $\Delta Q = 6pC$, and $V_g = 0.42V$ [61].

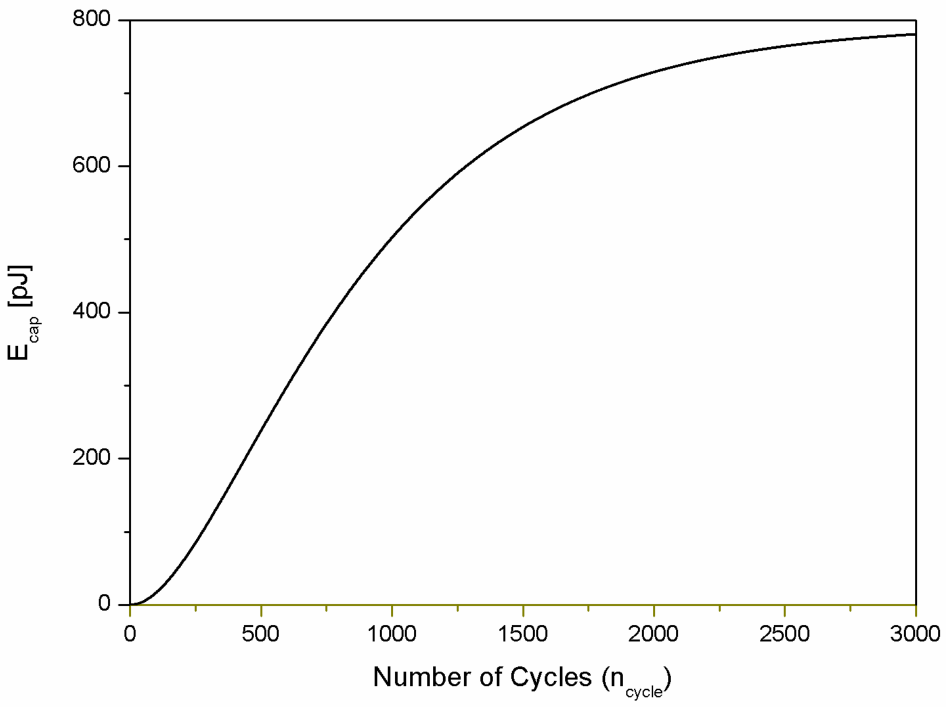


Figure 4-2: Energy harvested in the ultra-nano-capacitor as a function of the number of cycles.

Hence, the energy harvested by one nano-node in its capacitor E_{cap} can be computed as a function of the number of cycles n_c. Then we have

$$E_{cap}(n_c) = \frac{1}{2} C_{cap} V_{cap}^2(n_c), \tag{4.7}$$

where C_{cap} is the total capacitance of the ultra-nano-capacitor and V_{cap} is obtained from (4.6).

Fig. 4-2 shows how the amount of energy harvested by a nano-node in a BANN varies with the number of compressed-release cycles. We can see from Fig. 4-2 that for a nano-node in a BANN, its fully charged energy E_{full} is about $800pJ$. Hence, we set that all the nano-nodes are fully charged ($800pJ$) when the network is initially built in the human body. Thus, the available energy for a nano-node in the BANN $E_a(T)$ after the network runs T time units (generally in second) from the beginning can be formulated as

$$E_a(1) = E_{full} - \mathbf{1}_{fb}(1) \cdot E_{fb} - \mathbf{1}_{fb}(1) \cdot \mathbf{1}_{ans}(1) \cdot E_{ans} + E_{cap}(1), \tag{4.8}$$

$$E_a(T) = E_a(T-1) - \mathbf{1}_{fb}(T) \cdot E_{fb} - \mathbf{1}_{fb}(T) \cdot \mathbf{1}_{ans}(T) \cdot E_{ans} + E_{cap}(T), \quad T = 2, 3, \cdots \tag{4.9}$$

where $\mathbf{1}_{fb}(T)$ and $\mathbf{1}_{ans}(T)$ are the indicator variables which equal to 1 if the nano-node transmits the feedback message and answer message during the $T-th$ slot, respectively, otherwise they equal to 0. $E_{cap}(T)$ denotes the energy harvested during the $T-th$ slot. Here, we assume that the compress-release process of the nano-wire in the nano-node occurs one time per second as the heartbeat represents the energy source.

4.3.2 Average Path Loss

We let A (in db) denote the path loss of a traveling wave in the terahertz band, which is the sum of spreading loss A_s and molecular absorption loss A_{abs} [30]. Then we have

$$A(f,d) = A_s(f,d) + A_{abs}(f,d), \tag{4.10}$$

$$A_s(f,d) = 20\lg\left(\frac{4\pi f d}{c}\right), \tag{4.11}$$

$$A_{abs}(f,d) = k(f)d10\lg e, \tag{4.12}$$

where d is the path length, f is frequency of the electromagnetic wave, $k(f)$ is the absorption coefficient and c stands for the speed of light in the vacuum. Combining (4.10), (4.11) and (4.12), we can get the path loss of selected nano-node. It should be pointed out that in the terahertz band, the spreading loss is considerably large, limiting the maximum transmission range. However, we consider the extreme path loss observed for such transmission distances, which is mainly affected by molecular absorption in the human body. This is due to the fact that the blood is mainly made up of water.

4.4 Simulation Results

In this section, we conduct extensive network simulations to illustrate the performance of the proposed data collection mechanism in a BANN, and also discuss the impacts of network parameters on the average available energy and average path loss. As a benchmark scheme, the greedy scheme proposed in [47] is also simulated under the more practical BANN scenario with the consideration of path loss, to demonstrate the network performance improvement brought by the proposed scheme.

4.4.1 Simulation Settings

For illustrating the performance of the proposed data collection scheme, we developed a dedicated C++ simulator to simulate the external request generation process, movement of nano-nodes and the data collection process in a BANN. We set the network length $L = 300mm$ and width $W = 1mm$ in the whole network area. Moreover, similar to the settings in [47], the blood speed is set as $20cm/s$, the size of messages exchanged within the BANN is set as $M_a = M_e = 48bits$ and $M_r = M_s = 96bits$. Due to the blood is mainly made up of water, we set the electromagnetic frequency as $300GHz$, and the absorption coefficient is $123cm^{-1}$ [82]. Other network parameters are set as follows: the nano-node density $\mu = \{1, 4\}$ per mm^2, the arrival rate of external requests $\lambda = \{0.05, 0.10, 0.15\}$ per slot, and the length of wake-up region l ranges from $1mm$ to $10mm$. It should be pointed out that in order to conduct a more suitable comparison between the two schemes, we also introduce the wake-up region into the greedy scheme, while the original greedy scheme can be regarded as the case that l tends to L.

4.4.2 Simulation Results

First, we explore the performance of energy consumption of the proposed data collection scheme, and provide plots in Fig. 4-3 that how the average available energy varies with the length of wake-up region l under various settings of external request arrival rate and nano-node density. In general, we can see from Fig. 4-3 that the average available energy of the proposed data collection scheme is higher than that of the greedy scheme under all the cases, indicating that the proposed scheme can improve the performance of a BANN in the sense that it reduces the energy consumption. More specifically, we can see that as the length of wake-up region l increases, the average available energy under all the cases decreases, and thus the energy of the original greedy scheme serves as a lower bound for that of the proposed scheme. This is due to the fact that the larger wake-up region, the more nano-nodes would be activated and send feedback message, resulting in more energy consumption.

Moreover, it is worth noting that although both the two schemes are executed under the scenario with wake-up region, our scheme still outperforms the greedy scheme. This is because that our scheme will select the nano-node with the maximal estimated energy after transmitting the answer message, while the greedy scheme will select the nano-node with the maximal available energy before transmitting the answer message. Fig. 4-3 also shows the impacts of other key network parameters on the energy performance of a BANN. We can observe that a higher external request rate (a larger λ) will lead to less average available energy (more energy consumption), while the average available energy can be improved by increasing the nano-node density, especially for the scenario with a larger λ.

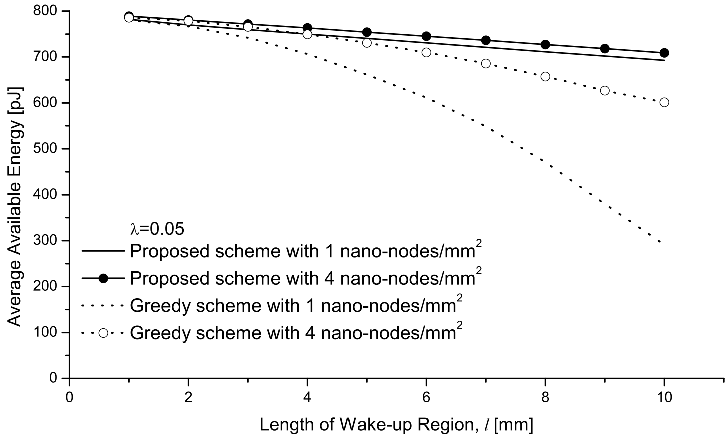
We further investigate the quality of the collected data of the proposed scheme. To this end, we summarize in Fig. 4-4 that how the average path loss varies with the length of wake-up region l under various settings of external request arrival rate and nano-node density. As illustrated in Fig. 4-4, we can see that the average path loss of the proposed scheme is much lower than that of the greedy scheme under all the cases, indicating that the proposed scheme can improve the quality of the collected data in a BANN. It is worth noting that as l increases, the average path loss of the greedy scheme increases, indicating that the path loss of the original greedy scheme serves as an upper bound (i.e., the worst quality of the collected data) for that of the scheme with the sleep/wake-up mechanism.

A more careful observation of Fig. 4-4 shows that as l increases, the average path loss of the greedy scheme increases linearly, while that of the proposed scheme increases a little and keeps almost constant. This is because that the greedy scheme will select the nano-node with the maximal available energy and this nano-node would appear in any location of the wake-up region, thus the expected distance between the selected nano-node and the nano-router increases as l increases; while the proposed scheme will estimate the energy consumption when it selects the nano-node, thus the expected distance between the selected nano-node and the nano-router (which dominates the possible energy consumption) is relatively stable, especially for the case with a large node density, the proposed scheme can always find a suitable nano-node in the near region of the nano-router such that the average path loss can keep constant as l increases.

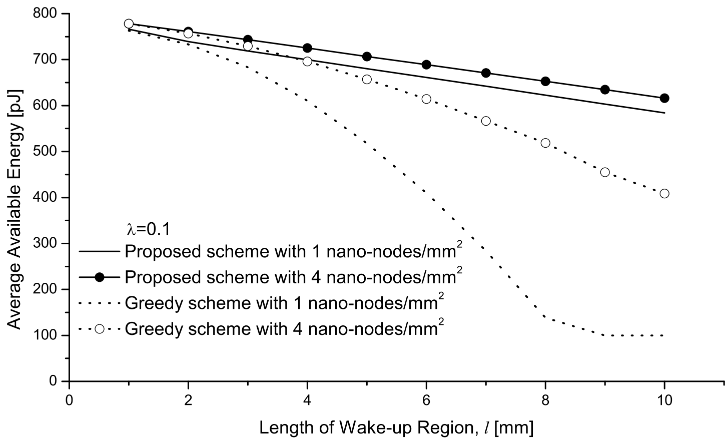
Regarding the impacts of other key parameters on the performance of path loss, we can see from Fig. 4-4 that the external request arrival rate λ has little impact since it is almost independent of the data collection process. Moreover, the nano-node density μ has almost no influence on the path loss performance of the greedy scheme, however, increasing μ can improve the path loss performance of the proposed scheme remarkably.

4.5 Summary

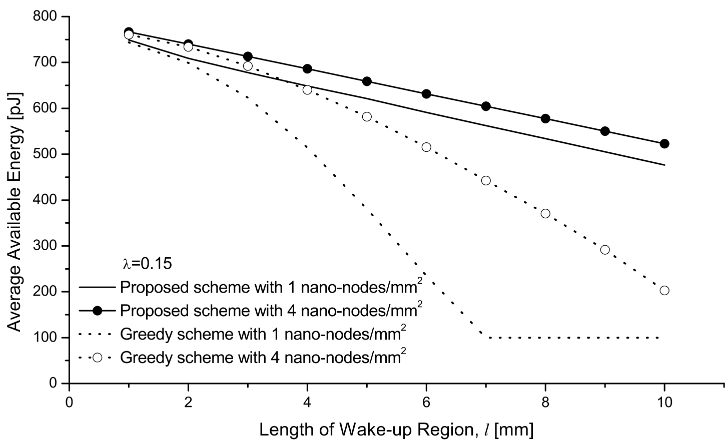
This paper proposed an energy-efficient data collection scheme for a practical Body Area Nanonetwork with the consideration of transmission path loss. Under this network scenario, the energy consumption of data collection is largely determined by the distance between the nano-nodes and nano-router. Thus, we first intentionally introduced a wake-up region to reduce the set of feasible nano-nodes which could be selected to collect and send the external requested information. We then adopted a novel nano-node selection strategy to select the node with the maximal remaining energy after the data collection process, which further saved the energy consumption and explicitly improved the transmission quality. Finally, simulations were conducted for both the the proposed scheme and the benchmark greedy scheme. The results demonstrated the efficiency of the proposed scheme in terms of its average available energy and average path loss.



(a) arrival rate of external requests $\lambda = 0.05$

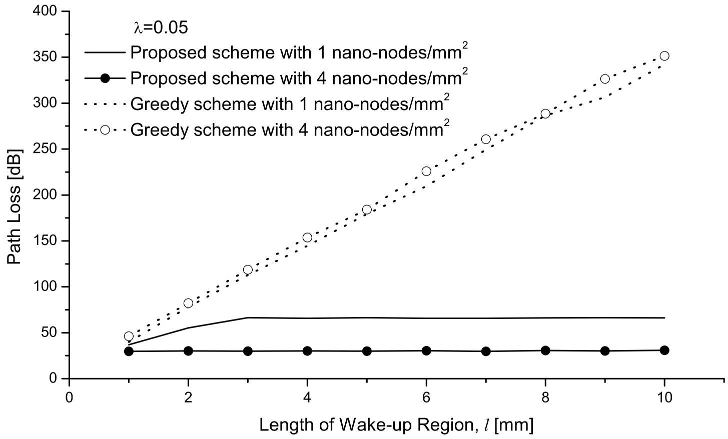


(b) arrival rate of external requests $\lambda = 0.1$

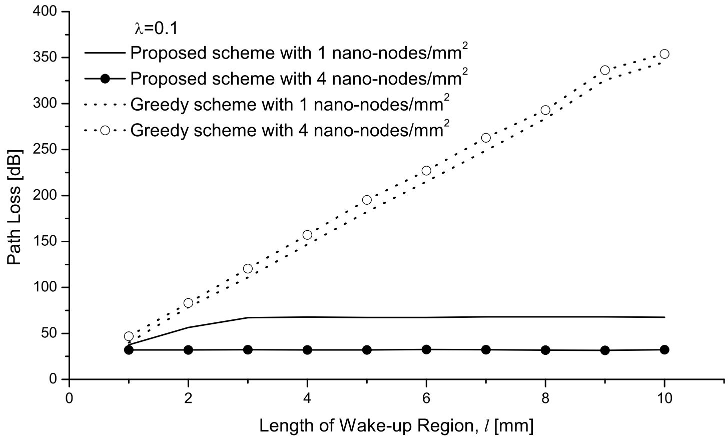


(c) arrival rate of external requests $\lambda = 0.15$

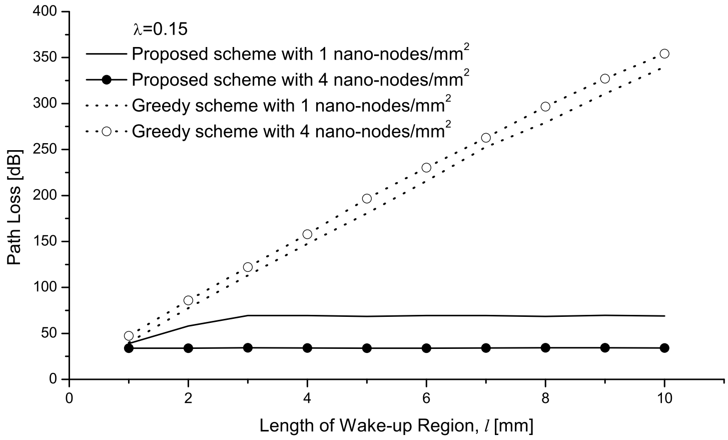
Figure 4-3: Simulation results for the performance of average available energy.



(a) arrival rate of external requests $\lambda = 0.05$



(b) arrival rate of external requests $\lambda = 0.1$



(c) arrival rate of external requests $\lambda = 0.15$

Figure 4-4: Simulation results for the performance average path loss.

Chapter 5

Timing-based Energy-efficient Data Collection Scheme in BANNs

This chapter focuses on the design of an timing-based energy-efficient data collection scheme with multiple nano-routers in BANNs. First, based on limited energy constraints, we are categorizing data as emergency data (ED) and normal data (ND). Then, we further use this classification for generating distinct packets and assigning priorities. Usually, the system transfers normal data (ND) regularly, and also sends emergency data (ED) immediately. Finally, we present extensive simulation and numerical results to validate our scheme.

5.1 System Model

This section presents the system models and main notations involved in this paper.

As illustrated in Fig. 5-1, we consider a BANN distributed along the artery of a human arm, which is assumed to be a rectangle area with length L and width W. The network consists of one nano-interface, n nano-routers vertically placed at a mutual distance D, and multiple nano-nodes with density μ. The nano-interface and nano-routers are assumed to be static, whereas all nano-nodes move at a constant speed along the artery following the direction of the blood. The network area is assumed to have torus boundaries such that when a nano-node reaches a boundary, it

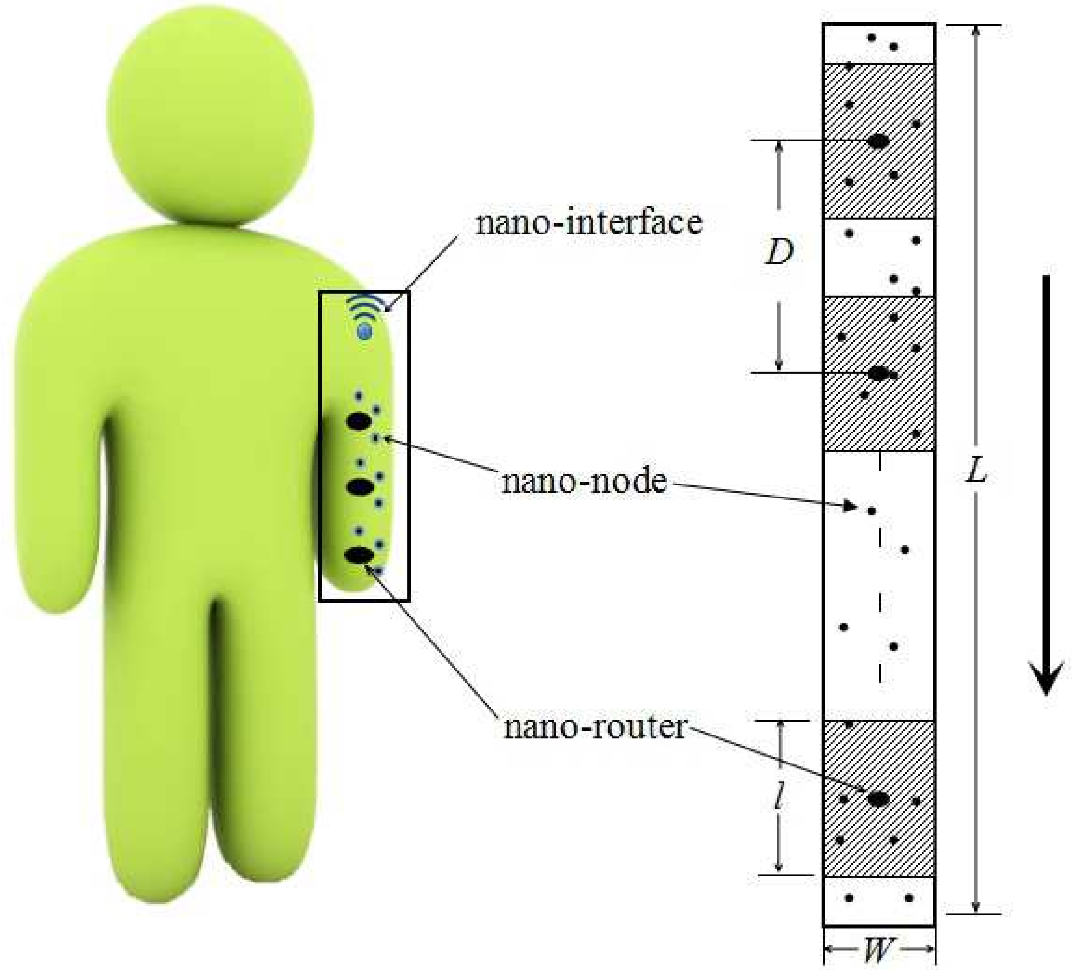


Figure 5-1: Illustration of system model

will move across the boundary and appear in the opposite side. The communication between different nano-machines is over the electromagnetic waves in terahertz band [15, 70, 83]. Through receiving the requests and commands from external entities, this network is able to perform various in-body tasks, like health monitoring, disease detection and drug release.

Nano-nodes are deployed for sensing data continuously and each nano-router gather sensed data periodically in their respective regions. Since all the sensed data does not have equal importance, therefore, we have categorized data into two different types emergency data (ED) and normal data (ND). Threshold u is used for differentiating emergency data from normal data and it is set according to the nature

Table 5.1: Main notations

Symbol	Definition
M_r	size of request message
M_h	size of the activation message
M_e	size of the energy feedback message
M_s	size of the answer message
E_{btx}	energy required to transmit a pulse
E_{brx}	energy required to receive a pulse
$E_{tx}(x)$	energy required to transmit a packet of x bits
$E_{rx}(x)$	energy required to receive a packet of x bits
E_{fb}	energy consumed for a nano-node transmitting the feedback message
E_{ans}	energy consumed for a nano-node transmitting the answer message
E_{full}	fully charged energy for nano-node
E_{th}	energy threshold
E_i	available energy for $nano - node_i$
V_{cap}	total capacitance of the ultra nano-capacitor
n_c	number of compress-release cycles
V_g	generator voltage
ΔQ	harvested charge per cycle
L	length of the rectangular area
W	width of the rectangular area
$D_{n,r}$	Distance of nano-node with respect to nano-router $\in$ r
NT_r	Neighbor table of each nano-router $\in$ r
R	transmission region of each nano-router
E_l	the energy level of nodes
λ	arrival rate of the external requests to the nano-interface
f	frequency of the electromagnetic waves
μ	density of nano-nodes

of the collected information. If the sensed value reaches to u then it is considered as ED and needs to be reported immediately. Whereas, any value that is lower than the predefined threshold u, is marked as ND.

The main notations of this chapter are summarized in Table 5.1

5.2 Timing-based Energy Efficient Data Collection Scheme

The network layer is responsible for addressing and routing problems. In BANN, nano-nodes have limited transmission range and inadequate energy resources for carrying out routine information. Nano-nodes are continuously sensing and transmitting information. Whereas, sensed information might have unequal importance. When traffic load is increased, there is a good chance of losing critical information, as no specific mechanism is defined for protecting such information. To tackle these issues we have developed a routing protocol. This protocol not only efficiently handles routine information flow but also provide mechanism for delivering critical information timely.

5.2.1 Timing/priority Mechanism

As mentioned before, in our energy-efficient data collection scheme, we first introduce a timing/priority mechanism for saving the unnecessary energy consumption. Based on categorization of data (ED,ND), Emergency Packet (EP) and Regular Packet (RP) are employed to transmit the information. EP and RP along their priority are briefly discussed below:

- **Emergency Packet (EP):** Emergency packet contains the emergency data. They have been assigned highest priority.

- **Regular Packet (RP):** Regular Packet are used for handling routine information. Inside RP, instead of sending the complete information, we are using flag to notify receiver about usual flow. This will considerably reduce the size of RP as well as redundant information flow. Nano-nodes will keep sending RP for each request unless it meets the threshold u. Consequently, smaller size of RP leads to significant decrease in the energy consumption for transmitting and receiving routine packets. Moreover, small size leads to low average processing time for RP. As RP consumes insignificant time during packet transmission, it results in minimum processing delay (T_{pd}). Since RP does not contain any alarming information they are treated as low priority packets.

Packet priority is assigned for data transmission. In this way, when an EP is received, it is immediately transmitted instead of waiting in the queue. On the other hand when it is RP's turn in the sending queue and EP has been received having higher priority than EP will be delivered first and after that RP will be entertained. Incase of congestion high priority packets have once more high importance. If nodes buffer overflow then packets with low priority are dropped only.

5.2.2 Neighbor Discovery

Handshake mechanism is performed for neighbor discovery. During neighbor discovery, nano-router will send M_h to all the neighboring nodes in its transmission range. Neighbor discovery mechanism helps in differentiating active nodes from invalid nodes. Any node can participate in neighbor discovery until its energy is greater than threshold E_{th}, E_{th} can be computed using the equation.

$$E_{th} = E_{rx}(M_r) + E_{th}(ED), \tag{5.1}$$

Here $E_{rx}(M_r)$ shows the energy required for receiving M_r and $E_{tx}(ED)$ represents the energy needed for sending ED . In order to contribute in data reporting, nano-node must have enough energy to transmit ED as ED has the larger size. If nodes energy level is less than E_{th} then it will wait unless it has regained the energy using energy harvesting mechanism. On the other hand, if a nano-node has sufficient energy for handling data aggregation responsibilities then it will send M_e as a response to the M_r. Algorithm 2 describes the mechanism applied for neighbor discovery.

5.2.3 Participating Nodes

In our proposed data collection strategy, nano-routers collect data periodically in their respective regions. Nano-router calculates selection score of each nano-node in its region. Nano-node selection score is determined for nominating nodes that can participate in data reporting, these selected nano-nodes are called participating nodes. In every interval T_x , total number of participating nodes varies according to the density of nano-nodes in respective region.

Nano-router selects participating nodes on the basis of their available energy (E_n),

Algorithm 2 Neighbor Discovery

r = List of nano-routers
n = List of nano-nodes
M_h = Neighbor Discovery Message
M_e = Energy Feedback Message
$D_{n,r}$ = Distance of nano-node with respect to nano-router $\in$ r
NT_r = Neighbor table of each nano-router $\in$ r
R = Transmission region of each nano-router
E_n = Energy of nano-node
Data: n, R
Result: NT_r
Each nano-router $\in$ r broadcast M_e to N in its R
for Each nano-node in the transmission region **do**
    if n $\in$ R **then**
        send M_e
    end if
end for
if r receive M_e **then**
    $NT_r \leftarrow n,\ D_{n,r},\ E_n$
end if

distance from the router ($D_{n,r}$), and on the frequency of selection (F_s) as participating node in the past. This approach helps in selecting only those nodes that not only have high energy but also have less distance from the router. F_s ensures that opportunity to be selected as participating nodes circulate among all nodes, instead of repeatedly selecting the same nodes. Thus, the energy level of nodes E_l can be written as:

$$E_l = \begin{cases} \frac{E_n}{D_{n,r}+F_s}, & \text{if} \quad E_n > E_{th} \\ 0, & \text{otherwise} \end{cases} \tag{5.2}$$

Using this tactic instead of waking up all the nodes in interval T_x , nano-router awakes only participating nodes. State of participating nodes change from sleep to active and they send the observed data as mentioned in algorithm 3.

Algorithm 3 Selection of Participating Node

N_{s-list} = Node-ID and E_l
N_{max} = Number of participating nodes to be selected
for Each nano-node $\in NT_r$ **do**
    $N_{s-list} \leftarrow$ Calculate the E_l using equation (5.2)
end for
sort N_{s-list} into descending order
$N_{max} \leftarrow$ (size of N_{s-list})/2
for 1 to N_{max} **do**
    Send (M_r)
end for

5.3 Performance Evaluation

This section critically analyzes the energy consumption and delay experienced in our proposed scheme.

5.3.1 Energy Analysis

We suppose that E_{btx}, E_{brx}, $E_{tx}(x)$ and $E_{rx}(x)$ are the energy required to transmit a pulse, receive a pulse,transmit a packet of x bits and receive a packet of x bits, respectively. We have used time spread on-off keying (TS-OOK) modulation scheme. In this scheme the presence of a pulse in a transmitted message for a specific duration shows bit 1, on the other hand, its absence shows bit 0 [8]. In TS-OOK modulation there is only a little chance of collision between femtosecond-long pulses because the time interval between transmissions is greater as compared to the pulse duration. Hence many nano-nodes can concurrently utilize the channel without any collision. The energy required for transmitting a pulse is E_{btx} , and energy needed for receiving a pulse is E_{brx} which equals to $0.1pJ$. However, during transmission, the energy is consumed only when it transmits a pulse (i.e bit 1) but for the receiving energy it is consumed for receiving both bits that are 0 and 1. Energy consumed for transmitting and receiving is expressed in equation (5.3), (5.5), where α shows the probability of having bit 1 within the x stream of bits.

$$E_{tx}(x) = x \cdot \alpha \cdot E_{btx}, \tag{5.3}$$

$$E_{rx}(x) = x \cdot E_{brx} = 0.1 \cdot x \cdot E_{btx}, \tag{5.4}$$

The available energy of $nano - node_i$ after interval T_x is calculated using equation (5.5). The value is obtained by considering previous energy E_0, energy consumed in receiving the request message and sending a response message. It is denoted using $E_{rx}(M_r)$ and $E_{tx}(M_s)$ respectively. Energy required for packet transmission increase or decrease with respect to the packet size. Hence, energy consumed for transmitting answer message $E_{tx}(M_s)$ is greater or smaller on the basis of answer message. If RP is transmitted then energy consumption is less, whereas, it increases for EP transmission.

$$E_i(T_x) = E_0 - E_{rx}(M_r) - \beta E_{tx}(M_s)(EP) - \beta E_{tx}(M_s)(RP) + H_i(T_x), \tag{5.5}$$

Where variable β is set as 1 if the node is selected as a participating node during time interval T_x. If node is not selected as a participating node then $\beta = 0$. M_s represents the transmitted answer packet in bits, whereas EP and RP denote the type of M_s. Incase transmitted packet is EP then EP is set to 1 otherwise 0, the same is as the case for RP. The harvested energy for interval T_x is given as $H_i(T_x)$, which is computed as follows:

$$H_i(T_x) = E_{cap}(n_{c,i} + f/\Delta T_x) - E_{btx}(0.1M_r + \beta M_s(EP + RP)), \tag{5.6}$$

Where E_{cap} is the accumulated energy given in equation (4.7), $n_{c,i}$ is the number of charging cycles required to reach by the ith node, $f/\Delta T_x$ shows the number of recharging cycles between two consecutive intervals.

5.3.2 Delay Analysis

The section analyzes the delay performance which is defined as the time duration that a packet experiences from source to its destination. Delay experienced by a packet can be determined by calculating the following components:

- T_ω: It represents processing delay (T_{pd}) encounter by the packets. Its value depends upon the packet size (P_s (bits)). Small packet requires less processing time, whereas, larger packets consumes more time in processing that results in comparatively larger delay. Smaller size of RP leads to insignificant processing time and helps in reducing delay.

$$T_\omega = P_s \cdot T_{pd}, \tag{5.7}$$

- T_ξ: It is influenced by P_s and packet priority as it induces queuing delay T_{qd}. Since RP have smaller size, consequently have smaller waiting time. Whereas, EP have high priority and they are immediately transmitted after receiving. Therefore, T_{qd} is very small for EP.

$$T_\xi = P_s \cdot T_{qd}, \tag{5.8}$$

- T_ε: T_ε is the delay caused by the distance and propagation speed, and it varies with respect to the distance and propagation speed.

$$T_\varepsilon = \frac{distance}{Propaation_{speed}} \tag{5.9}$$

- T_ν: T_ν express the transmission time of the packet. Transmission time can be computed using P_s and the link bandwidth as

$$T_\nu = \frac{P_s}{link_{bandwidth}} \tag{5.10}$$

The overall delay $delay_i$ experienced by the i_{th} packet can be expressed using the equation (5.11)

$$delay_i = T_\omega + T_\xi + T_\varepsilon + T_\nu \tag{5.11}$$

Small number of participating nano-nodes generate a few number of packets. Low packet generation rate causes low average delay as they reduce T_{pd} and T_{qd}. Average delay can be expressed as:

$$delay_{ave} = \sum_{i=1}^{n} \frac{delay_i}{n} \tag{5.12}$$

The nano-router is periodically collecting information from the deployed nano-nodes and reporting back to external healthcare monitoring system. In this way, if external monitoring system requires an urgent response then nano-router can immediately entertain the request as it is already keeping updated information at all the times. Hence the time consumes for responding an urgent query T_{req} is equal to the service time of router T_{rs} (times required by the router to look in its table).

5.4 Simulation Results

The proposed protocol stack for BANN architecture is evaluated under different network condition using NANO-SIM simulator [84] (i.e. an open source tool modeling WNSN and electromagnetic based communication in the terahertz channel). A comparison is made between the selective flooding and the greedy schemes proposed in [47]. In selective flooding scheme, when a nano-node receives a packet, it forwards the packet in the opposite direction to control forwarding of the same packet. Whereas, in the greedy scheme, when a request is received from external devices nano-node is selected for a response that has the highest energy.

5.4.1 Simulation Settings

In our experiments we consider nano-interface deployed at the center of the artery, whereas nano-routers are uniformly distributed inside the entire artery. Initially, nano-nodes are uniformly distributed along the artery and move along the artery following the direction of blood at the speed $20cm/s$ [47]. However, nano-interface and nano-routers maintain fixed position throughout the simulation.At the physical layer, a TS-OOK configuration is used with the pulse duration, pulse time interval and transmission range equal to $100fs$, $100ps$, and $10mm$ respectively. Each nano-node has an initial energy of $800pJ$ as stated in [85].

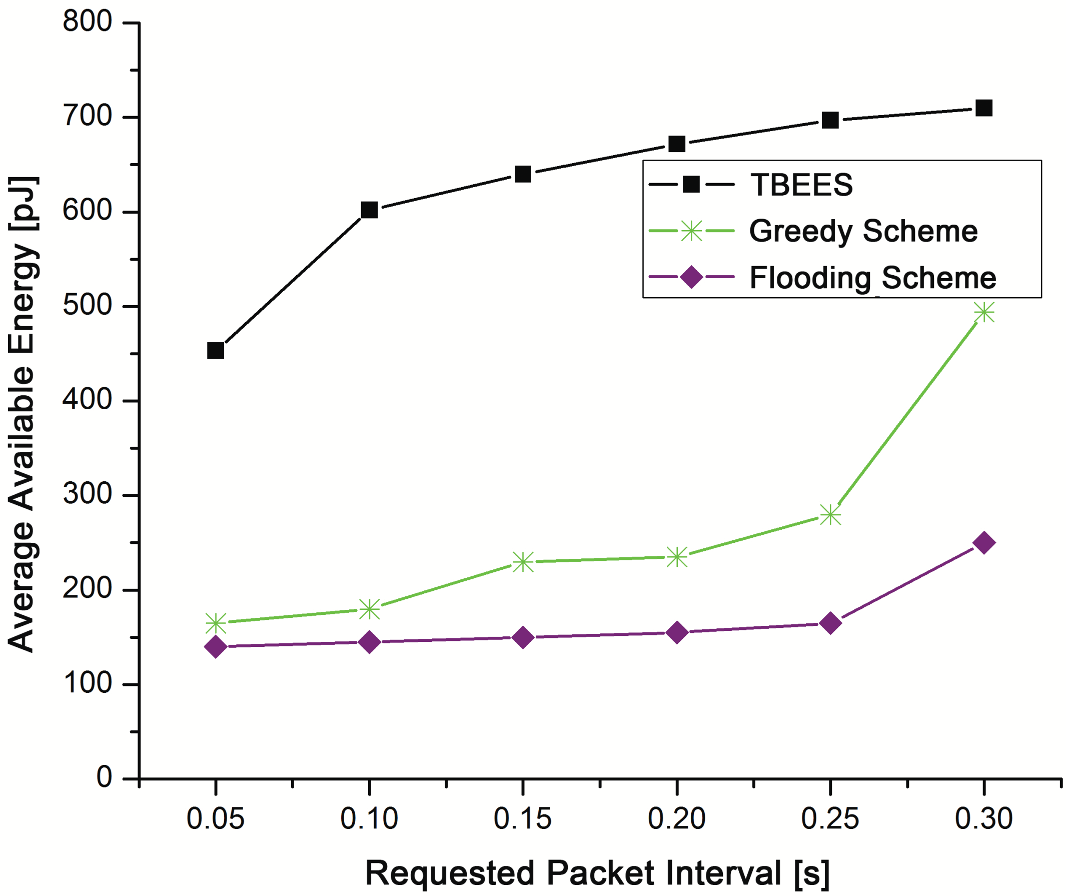


Figure 5-2: Average available energy comparison for TBEES, Greedy and Flooding schemes

5.4.2 Simulation Results

The average available energy is the most important metric for determining the efficiency of the protocol stack. The average available energy is evaluated by changing nano-router requested packet interval (RPI) from 0.05 to 0.3. From Fig. 5-2, it is evident when nano-router has lowest RPI that is 0.05, the energy is depleted rapidly as more energy is required for satisfying a large number of requests. However, when RPI increases average available energy also increases and can reach to 500pJ. Timing-based Energy-efficient Data Collection Scheme (TBEES) has lower energy consumption even the RPI is 0.05 because RPs highly influence energy conservation. Due to the small size of RP, nano-node consumes very low energy for data reporting. On the other

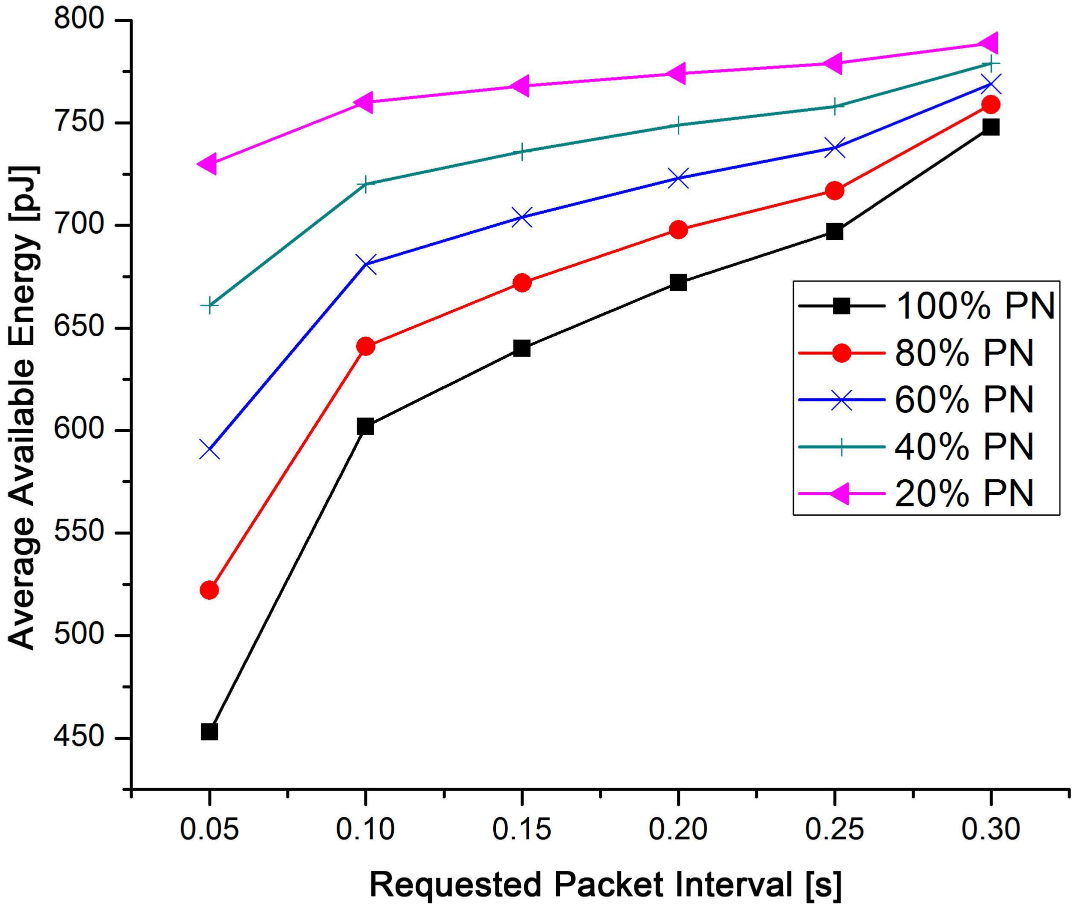


Figure 5-3: Average available energy comparison with respect to decreasing number of participating nodes

hand, selective flooding and greedy scheme have lower average energy as compared to TBEES for all RPI. Selective flooding has high energy consumption because when a request is received it is forwarded to all the nano-nodes and all nano-nodes suffer from energy loss due to data aggregation and packet forwarding. Greedy scheme also has high energy consumption because it selects the node having highest energy. However, in greedy scheme distance of nano-node from nano-router is not considered. When selected nano-node opt for answering the request message only on the basis of its energy, it may consume more energy due to its position.

The Fig. 5-3 demonstrates that maximum energy consumption is witnessed for high participating nodes and RPI . It is evident that, when maximum participating

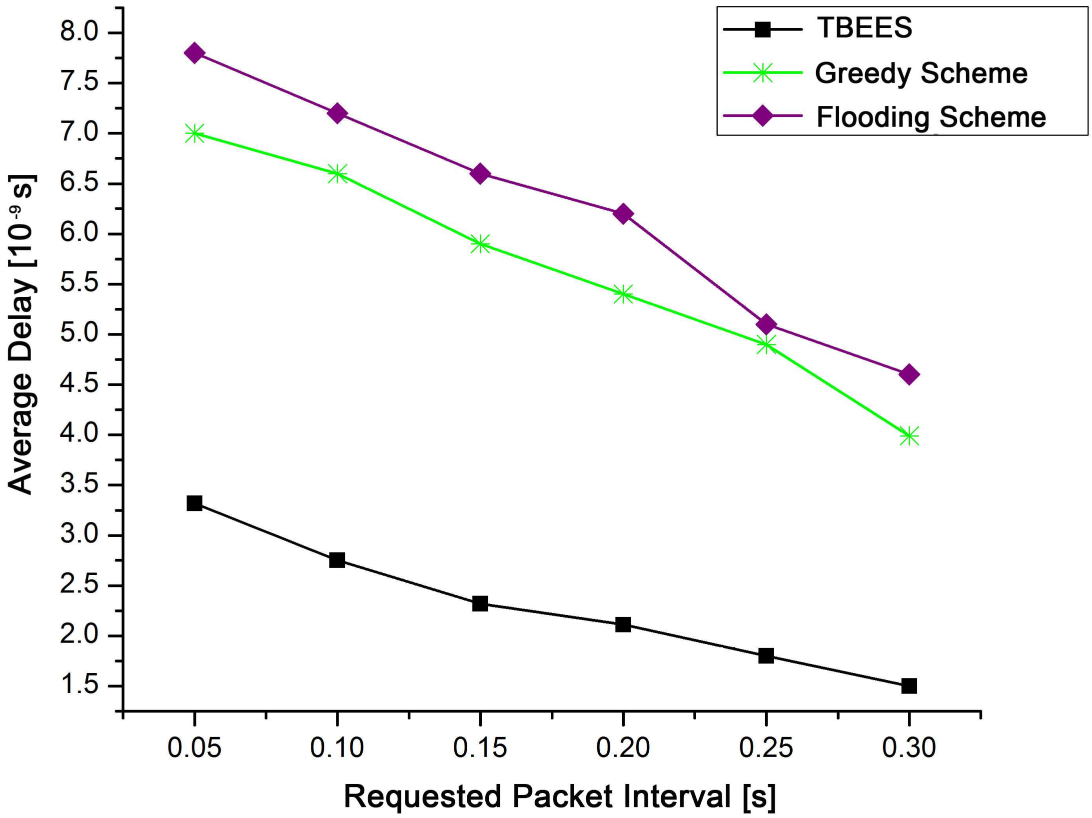


Figure 5-4: Average delay comparison for TBEES, Greedy and Flooding schemes

nodes are considered, the network also consumes utmost energy for all RPI (i.e. 0.05, 0.1, 0.2, 0.25 and 0.3) as compared to the lower participating nodes. All participating nodes show high energy consumption for lower RPI (0.05) and start conserving energy when RPI is increased. Therefore, for participating nodes lower energy consumption is observed at RPI 0.3, as low RPI is reducing the pressure of generating high traffic. When 40% of participating nodes take part in data reporting, they significantly help in energy preservation and the available energy is reduced to 661pJ , 720pJ , 736pJ , 749pJ , 758pJ and 779pJ for RPI 0.05, 0.1, 0.15, 0.2, 0.25 and 0.3 respectively.

According to the Fig. 5-4, when RPI is the minimum, network suffers from high delay as handling a large number of requests require more time. When RPI is increased it results in low delay since the number of requests coming from nano-router is decreased and nano-node can deliver the M_s timely. TBEES outperforms selec-

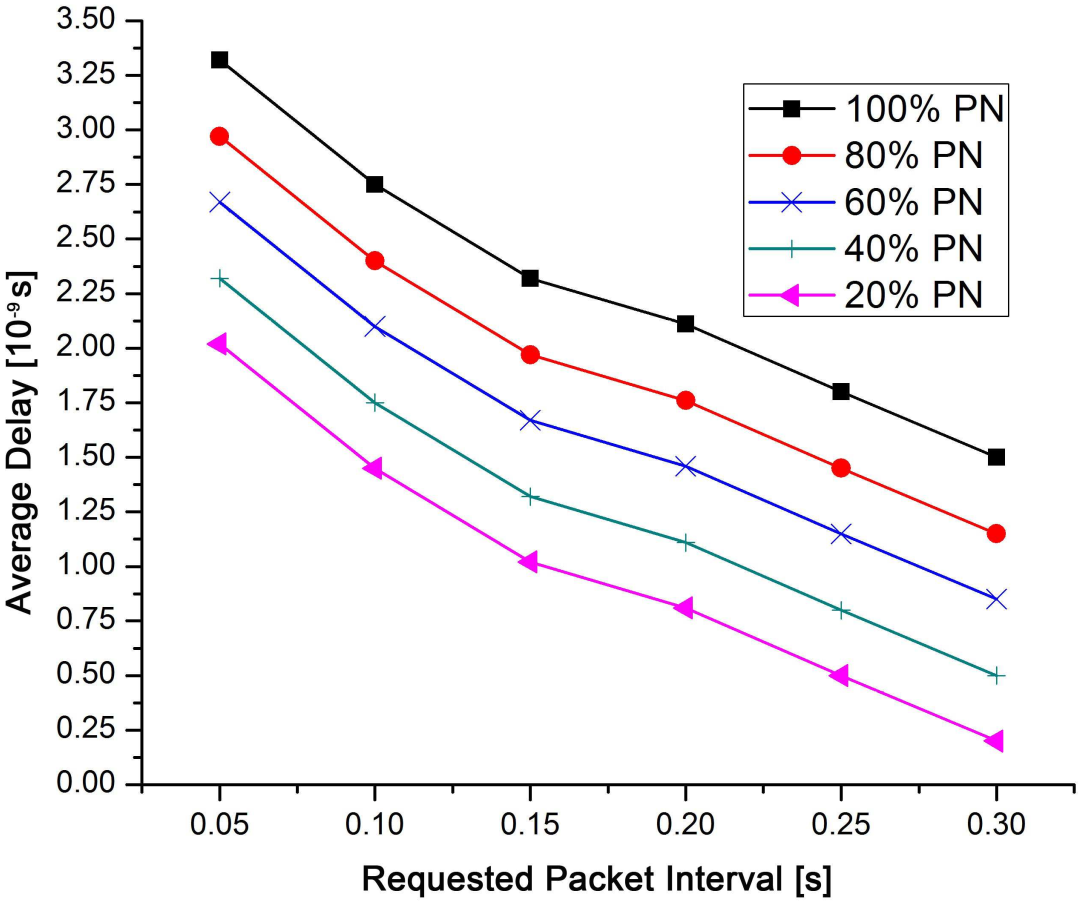


Figure 5-5: Average delay comparison with respect to decreasing number of participating nodes

tive the flooding and the greedy schemes in terms of delay as small packet size for data reporting results in low processing and service time. Moreover, EP packets have high priority that leads to low queuing delay. Selective the flooding and the greedy scheme have large delay as packet size is fixed and no mechanism is defined for handling emergency data.

The average delay is examined by the increasing number of participating nodes. From Fig. 5-5, we can deduce that when 100% participating nodes are used for data reporting at RPI 0.05, the average delay is higher. For the same RPI (i.e. 0.05) average delay started reducing for participating nodes. When participating nodes are decreasing the number of answer packets are also reduced, leading to low delay. At

RPI 0.05, when participating nodes are 80%, the average delay is $3 * 10^{-9}(s)$. A large number of nano-nodes participate in data reporting. When all these nano-nodes are sending answer messages to the nano-router, the traffic load will increase which will result in higher delay. Participating nodes 60% and 40% also experience the same issue, at low RPI large number of answer messages are generated, causing increase in the average delay. When RPI is increased, it has also influenced the delay confronted before. 20 participating nodes suffer from high average delay when RPI is 0.05 as compared to the decreased RPI(i.e. 0.1, 0.2, 0.25 and 0.3).

5.5 Summary

According to the detailed simulation analysis of TBEES, it is evident that TBEES provides 58% and 73% better average available energy than flooding and greedy schemes respectively. This is due to the use of RP that has significantly reduced the energy consumption in transmitting smaller number of bits. TBEES also improves delay by 63% as compared to flooding scheme and 59% with respect to the greedy scheme. The reason of reduced delay is that the smaller size of RP and smaller size leads to less T_{pd} and T_{qd}. In our proposed protocol TBEES, packet loss ratio is significantly reduced to 22%, whereas, it is observed as 40% and 31% in selective flooding and greedy schemes respectively. In order to explore the influence of decreasing participating nodes on network performance, we have presented the detailed comparison with respect to the increasing number of participating nodes. Results illustrate that low number of participating nodes provides better efficiency in terms of delay, energy conservation and packet loss.

TBEES is priority-based energy efficient protocol stack. TBEES uses nano-router for keeping external healthcare monitoring system updated by reporting periodic information. During each interval, participating nodes are selected that satisfies the selection criteria regulated by the nano-router. Participating nodes helps in reducing energy consumption for data reporting. In addition, different packet types (ND and ED) are proposed for collecting observed data. ND and ED have significantly reduced energy and delay experienced in transmitting routine information. Assigning high priority to EP has minimized the probability of losing critical information. Furthermore, it improves the time consumed for sending critical information.

Chapter 6

Relay-based Energy-efficient Data Collection Scheme in BANNs

In this chapter, we consider relay-based energy-efficient data collection scheme with minimum energy coding (MEC). Maximum nano-node density for reliable communication in BANNs is derived, and density dependent reliability analysis is conducted. Rate-delay and energy-delay are also investigated with constant codebook size and constant Hamming distance, separately. Finally, we provide extensive simulation and numerical results to validate our scheme.

6.1 System Model

The term ad-hoc nanonetwork is in general used to represent networks with no central controllers, opposed to cellular networks. These networks are studied in the literature for recent years, under different assumptions such as mobile nodes, or multi hop communications. Using ad-hoc in BANNs are first considered in [66]. In that work, the authors illustrate the challenges for the realization of CNT-based nano-scale networks.

The network considered in this work is given in Fig. 6-1. Nano-nodes do not forward codewords, different from classical relay-based networks, due to complexity considerations. A source nano-node attempts communication with a nano-node within its range of operation, r. The transmission range is used to obtain the max-

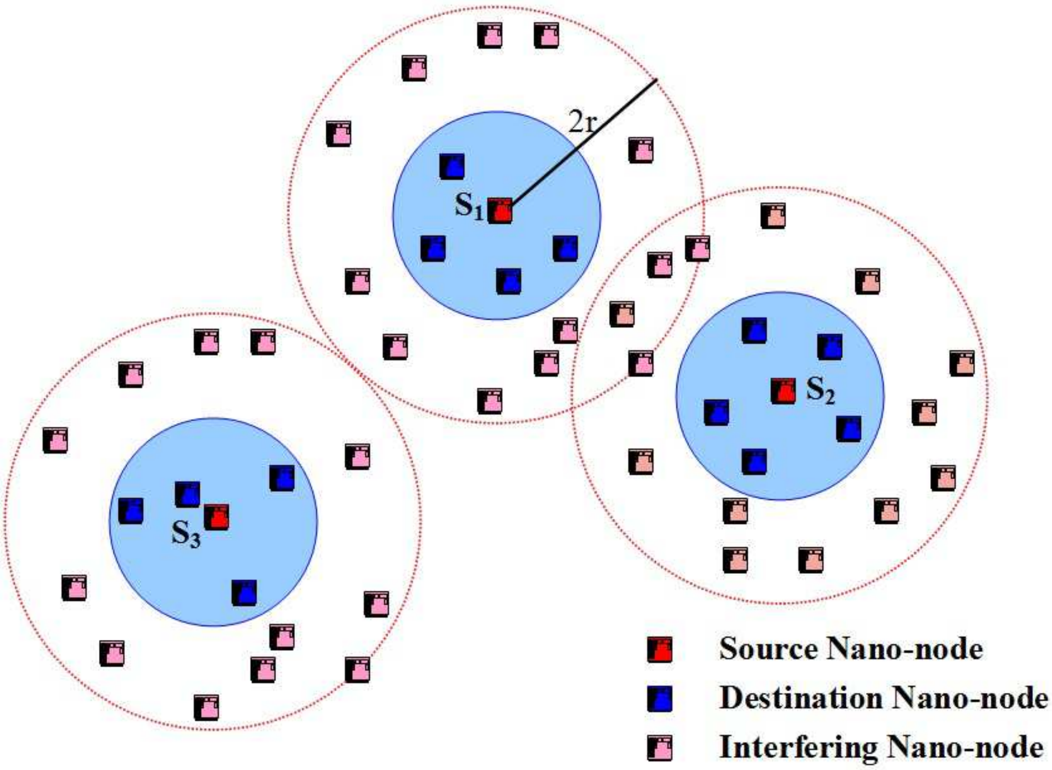


Figure 6-1: BANNs with potential destinations and potential interfering nano-nodes

imum node density in the relay-based nanonetwork. Destination nodes attempt to decode as many codewords as possible, without considering the source nano-node. Hence, no link is established between source and destination nano-nodes. Such a scenario applies to nano-sensor networks, in which a destination nano-node collects as much data as possible.

Errors are assumed to be due to collisions only, which is justified by keeping symbol error probability below 10^{-9}, by choosing the proper transmission distance for fixed transmission power. A CNT antenna is set to dissipate a power of $5uW$, which is currently the largest power level a CNT antenna can support [86]. In the symbol error probability calculation, only path loss and thermal noise are included as detrimental factors. Molecular absorption and molecular noise are ignored, since the selected modulation scheme uses allowable frequency windows in the THz band, in which molecular effects are negligible. Nano-nodes in the interference range are assumed to be distributed within an area of $2(2r)^2$, where r is the maximum distance, at which error probability of OOK modulated symbols does not exceed 10^{-9}. Since the transmission range of a nano-node is r, a destination within range can be compromised by nodes within $2r$ range. Hence, maximum number of nano-nodes supplied by MEC should be distributed within a range of $2r$. Choosing the band of operation as 1 THz and bandwidth as 10 GHz, r is easily found to be equal to 10^{-3} meters.

6.2 Minimum Energy Codes

In coding theory, a codebook is any selection of fixed length codewords, c_i's, which can be mapped to source symbols. Hamming weight of a codeword c_i is denoted with w_i, and is defined as the number of non-zero entries in the codeword. Hamming weight is equivalent to the number of 1 in the codeword for binary codes. Hamming distance between two codewords is defined as the number of bits that are different, whereas Hamming distance of a code, is the minimum of all Hamming distances.

In this paper, p_{max}, d and M represent the probability of most likely source outcome, code distance, and source set cardinality, respectively. As a precondition of the proposed minimum energy codes, an OOK modulation scheme with l carriers, each located at allowable frequency bands in the THz channel is proposed. In this paper, we assume $l = 1$ for simplicity. The analysis can be easily generalized to any l.

6.2.1 Minimum Expected Weight

In classical communication scenarios, both source coding and channel coding schemes are employed in general. Source coding reduces redundancies in the source symbols, whereas channel codes are used to add redundancy to combat channel noise and other detrimental factors. To ensure low complexity, our proposed technique does not employ any source coding mechanism. Another advantage of not using source coding is that, codewords to be used are not equiprobable in general, which can be exploited to reduce energy consumption on the average, using minimum energy codes. Our proposed minimum energy codes, MEC, yields the minimum average code weight, depending on the source distribution and desired reliability via Hamming distance. From [68], we know that

$$min(E(w)) = \begin{cases} (1-p_{max})d, & p_{max} > \frac{1}{2}, \\ \frac{d}{2}, & p_{max} < \frac{1}{2}, \text{if d even} \\ \lceil\frac{d}{2}\rceil - p_{max}, & p_{max} < \frac{1}{2}, \text{if d odd} \end{cases} \tag{6.1}$$

6.2.2 Codebook generation

Although different approaches exist to generate a minimum energy codebook, a simple and tractable scheme is proposed. With this approach, minimum codeword length is obtained as

$$n_{min} = d + (M-2)\lceil\frac{d}{2}\rceil \tag{6.2}$$

To ease the analysis, we stick with the assumptions in our previous work, and assume $p_{max} > 0.5$ and d is even.

A sample codebook generation can be given as follows: If p_{max} is greater than 0.5, all 0 codeword should exist in the codebook and be mapped to the most probable source outcome. In order to assure minimum Hamming distance, other codewords should be $weight - d$, since code distance is desired to be d. Codeword selection is more straightforward if $p_{max} < 0.5$. Let 1_k and 0_k represent a $length - k$ block of ones, and a $length - k$ block of zeros, respectively. Then the rows of the following matrix are codewords generated by the proposed mechanism for $p_{max} < 0.5$ and right hand side of the equation yields the case for $d = 4$.

$$\begin{bmatrix} 0_0 & 1_{\frac{d}{2}} & 0_{n-\frac{d}{2}} \\ 0_{\frac{d}{2}} & 1_{\frac{d}{2}} & 0_{n-d} \\ 0_d & 1_{\frac{d}{2}} & 0_{n-\frac{3d}{2}} \\ \vdots & \vdots & \vdots \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 & 0 & \cdots & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & & & & & & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 0 & 1 & 1 \end{bmatrix} \tag{6.3}$$

Where that 0_0 represents null vector with dimension 0.

6.3 Relay-based Energy-efficient Data Collection Scheme

The proposed algorithm has two main phases as depicted in algorithm 4. In the first phase, all nodes keep collecting one-hop and two-hop neighbor information by using standard ad hoc routing protocols (e.g. Optimal Scheduling and Power Allocation for Two-Hop Energy Harvesting [87]) in order to be added into one-hop and two-hop neighbor lists, respectively. Then, information contained in both neighbor lists are used to compute a current number of neighbors or N_c. In some situation, a node can be both one-hop and two-hop neighbors. In Fig. 6-2, v is both one-hop and two-hop neighbor of u, in this case, the algorithm considers v as one-hop neighbor of u only (assume that $N1$ and $N2$ are one-hop and two-hop neighbors of a node, respectively; $N1$ and $N2$ must not be duplicated when computing N_c).

Algorithm 4 Relay-based Energy-efficient Data Collection Scheme

Define N_d by setting K and r values, $K - r \leq N_d \leq K + r$
Compute $N_c = (\alpha * N1) + (\beta * N2)$
if $N_c = 0$ (no neighbor) **then**
    Adjust transmission power to maximum level
else if $N_c >$ upper bound of $N_d (N_c > K + r)$ **then**
    Decrease transmission power to next lower level
    (must not be lower than minimum level)
else if $N_c <$ lower bound of $N_d (N_c < K - r)$ **then**
    Increase transmission power to next higher level
    (must not be higher than maximum level)
end if

Moreover, the total number of one-hop and two-hop neighbors or N_c can be computed by using equation (6.4) as shown below:

$$N_c = (\alpha * N1) + (\beta * N2), \tag{6.4}$$

where α and β are weighted value which is either 0 or 1. Hence, this proposed topology control algorithm gives a flexible option to consider only either one-hop neighbor or two-hop neighbor, or both of them. To take into account only one-hop neighbor to

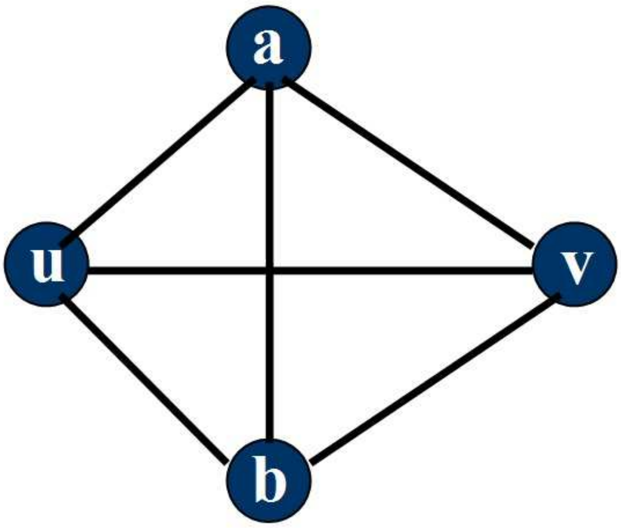


Figure 6-2: Example of a network topology with four nano-nodes.

compute N_c, $\alpha = 1$ and $\beta = 0$, and vice versa. In this work, we consider both one-hop and two-hop neighbor information to reduce the energy consumption and increase the network performances, then both α and β are consequently set to 1.

Furthermore, N_d is a ranged value of desired number of neighbors or node degree (K) and it is predefined value. Hence, $K - r \leq N_d \leq K + r$, where r is reliability factor used to prevent frequent change of transmission power which may result in route instability caused by highly dynamic topology. Note that in this work, K is set to 30 of the total nodes which corresponds to 15 desired neighbors out of 50 nodes, while r is set to two-third of K which is equal to 10. However, K can be configured to be lower in sparse networks or higher in dense networks in order to be well performed in various environments.

In the second phase, the algorithm keeps monitoring the number of neighbor N_c and transmission power will be dynamically adjusted according to the desired node degree N_d. In other words, the proposed topology control algorithm keeps maintaining the current number of neighbors N_c to be approximately matched with N_d. In case that $N_c = 0$ (no neighbor found), then transmission power will be immediately set to maximum level of transmission power to discover more neighbors in order to be connected to the networks. Furthermore, if the N_c is greater than upper bound of

N_d, the algorithm will typically decreases the transmission power to the next lower level to save energy; and in case that N_c is less than lower bound of N_d, the algorithm will dynamically increases the transmission power to the next higher level to achieve better network connectivity.

6.4 Performance Evaluation

Feasibility of nanonetworks depends on energy efficiency, robustness against highly dynamic conditions and self sustainability. It might not always be possible to implement central controller units in certain nanonetworking scenarios. In such cases, the communication scheme should provide reliable access to the channel. However, using complex medium access techniques is not feasible in nano-nodes due to the limited complexity. Moreover, popular spread spectrum multiple access techniques such as CDMA cannot be used, since the THz channel shows frequency selective characteristics, which would result severe distortion of the signal, when passed through the channel. It is proposed in [67] that, using low weight channel codes might drop the necessity of a medium access scheme. In this paper, the same idea is employed for the analysis of relay-based nanonetworks using MEC. It is expected that, as more and more nodes communicate with each other within the transmission range of a source node, successful communication probability decreases. For nanonetworks using MEC, discovering the maximum nano-node density is important, since it indicates the communication and computation capability of a nanonetwork within a given amount of area. Furthermore, rate-delay and energy-delay for relay-based nanonetworks are investigated.

6.4.1 Maximum Node Density

First, we analyze the successful codeword decoding probability at the destination nano-node. It is assumed that a nano-node attempts to transmission with probability of p. Instead of having nano-nodes transmitting continuously, nodes transmitting only when they require, not only reduces interference, but also the energy consumption.

s is the number of nodes within the interference range of the source nano-node. It is assumed that s neighbor nano-nodes exist within a distance of $2r$, when nano-nodes are uniformly distributed with density of

$$\rho = \frac{s+1}{2\pi(2r)^2}, \tag{6.5}$$

To assure reliability, the correct codeword decoding probability is derived. Probability that the transmitted bit is 1 is

$$\eta_1 = \sum_{i=1}^{M} p(1|c_i)p(c_i), \tag{6.6}$$

$$= \sum_{i=1}^{M} \frac{w_i}{n_{min}} p_i = \frac{E(w)}{n_{min}}, \tag{6.7}$$

using the law of total probability, where w_i is the weight of the codeword c_i that is mapped to source with probability p_i. In order the transmitted bit to be received by the destination properly, interfering nodes should either transmit 0 bit or not transmit at all. The probability that there is at least single node transmitting bit 1 within the interference range, i.e., p_x is

$$p_x = 1 - \sum_{i=0}^{s} \begin{pmatrix} s \\ i \end{pmatrix} (p\eta_0)^i (1-p)^{(s-i)}, \tag{6.8}$$

$$= 1 - (1 - p(1-\eta_0))^s, \tag{6.9}$$

where $\eta_0 = 1 - \eta_1$, i.e., the transmission probability of bit 0. Collision probability is non-zero only if 0 is transmitted by the source. If 1 is transmitted, as interference caused by other nodes cannot flip this bit, collision cannot occur. As a result, collision probability of the nano-node can be calculated as

$$p_c = \eta_1 0 + \eta_0 p_x = \eta_0 - \eta_0(1 - p(1-\eta_0))^s, \tag{6.10}$$

As previously discussed, symbol error probability is assured to be less than 10^{-9}, by choosing the transmission range. Hence, collision can be considered as the only error source, leading to simplified analysis of correct decoding probability. Eventually, since a maximum of $\lfloor \frac{d-1}{2} \rfloor$ collisions can be corrected, correct decoding probability at the destination, ξd, can be written as

$$\xi d = \sum_{i=0}^{\lfloor \frac{d-1}{2} \rfloor} \binom{n_{min}}{i} (p_c)^i (1-p_c)^{n_{min}-i}, \tag{6.11}$$

It can be concluded that, ξd converges to 1 with the increase of the Hamming distance, if $p_c < 1/M$. In other words, reliable communication can be achieved if collision probability is less than the inverse of source set cardinality. For simplicity, assume $p_{max} < 0.5$ and d is even. Using (6.1), (6.2), (6.6) and (6.10), we reach to the condition.

$$1 - [1 - \frac{p}{M}]^s < \frac{1}{M-1}, \tag{6.12}$$

$$p < M \left[1 - \left(\frac{M-2}{M-1} \right)^{1/s} \right], \tag{6.13}$$

(6.13) gives the relation between p, M, and s, i.e. node transmission probability, source set cardinality, and number of neighboring nodes, for which reliable communication is possible with MEC. It is easily seen that, expression on the right hand side of (6.13) decreases with increasing M. Hence, we can take the limit of (6.13) to obtain an upper bound for p, valid for any M, to achieve reliable communication.

$$p_{lim} < \lim_{M\to\infty} \sum_{k=1}^{\infty} C(\frac{1}{s}, k) \frac{(-1)^{k+1} M}{M-1} = \frac{1}{s}, \tag{6.14}$$

where the general binomial coefficient for $k > 0$ is

$$C(\frac{1}{s}, k) = \frac{1}{k!} (\frac{1}{s})(\frac{1}{s} - 1) \cdots (\frac{1}{s} - k + 1), \tag{6.15}$$

It is concluded that $p < 1/s$ is the required condition, satisfying (6.13) for any M. Hence, MEC supplies an relay-based nanonetwork having s neighbor nodes, only if nodes transmit with probability less than $1/s$. Interpreting the result from the other side leads to the desired bound for maximum node density. Maximum number of nodes within the interference range should be less than $1/p$. This corresponds to the density

$$\rho_{max} = \frac{\lfloor 1/p \rfloor + 1}{A_{tr}} = \frac{\lfloor 1/p \rfloor + 1}{8\pi} mm^2, \tag{6.16}$$

where A_{tr} is the transmission area.

6.4.2 Rate-Delay and Energy-Delay

Rate-delay tradeoff of networks is vastly investigated in the classical communication scenarios. In most communication scenarios, capacity is achieved with infinite delay. This makes the rate-delay tradeoffs worthy of investigation, to uncover the rate achievable with finite delay. The same idea applies in nanonetworks using MEC. Different from classical scenarios, energy dissipation should also exist in this picture, as it is one of the most important metrics for nano-communications. As no retransmission or channel contention exists, delay is solely due to codeword length, ignoring propagation delay, since transmission range of nano-nodes is very small. Hence, delay is given as

$$\delta = n_{min} T, \tag{6.17}$$

where T is the symbol duration. Due to the used modulation technique, $T = 10ps$. Additionally, we provide a different rate definition as

$$R = \xi_d log M, \tag{6.18}$$

(6.18) is the expected amount of information correctly decoded at the destination nano-node. Without an information theoretic approach, this definition provides a simple and insightful way to investigate rate-delay tradeoffs in relay-based nanonetworks. Average energy per codeword depends on average weight, since OOK-based modulation at available THz windows is used. It is formulated as,

$$\epsilon = E(w) PT, \tag{6.19}$$

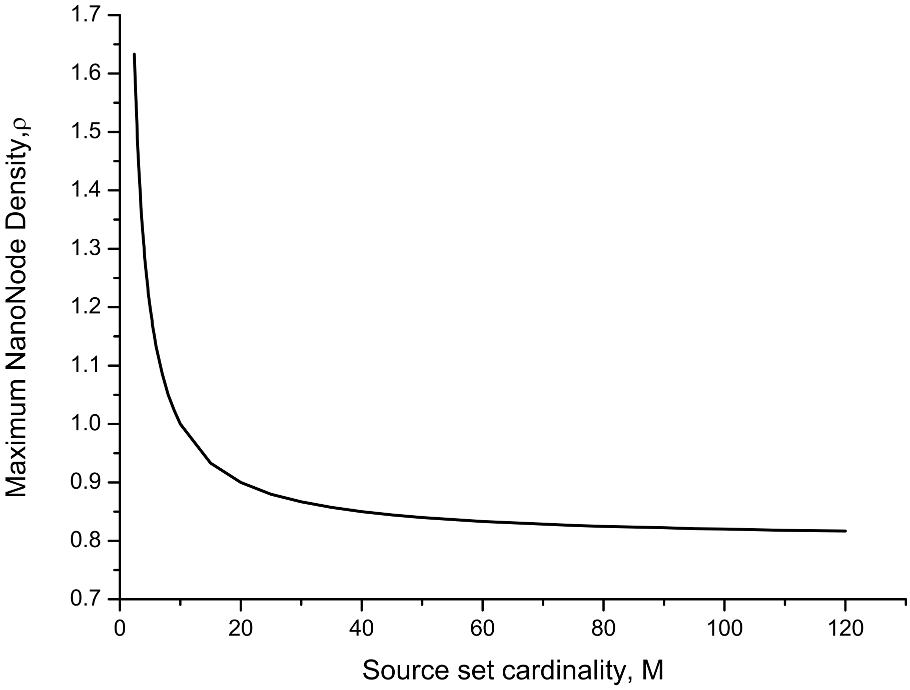


Figure 6-3: Maximum allowed node density vs. source set cardinality for p=0.05

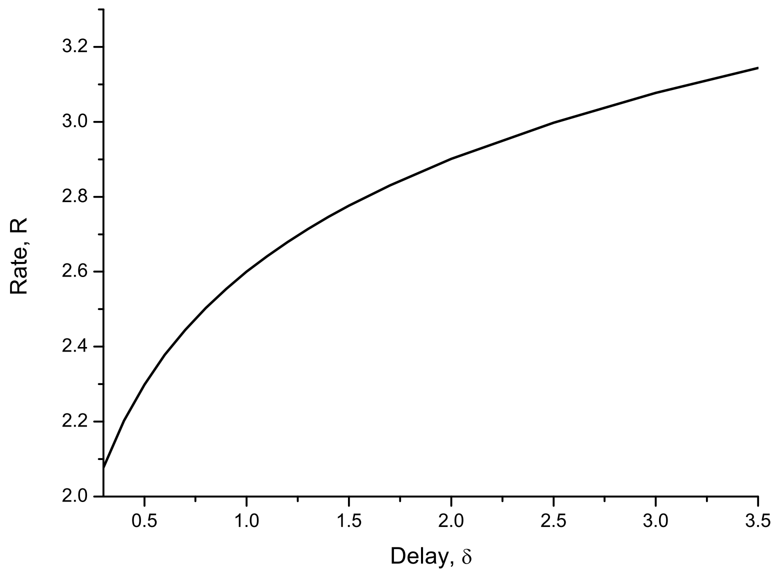
where P is the symbol power. Due to the power limits of CNTs, $P = 5uW$.

As given in equation (6.2), codeword length depends on d and M. We use two different approaches to reveal rate-delay tradeoffs. In both approaches, we assume that $p = 1/s$.

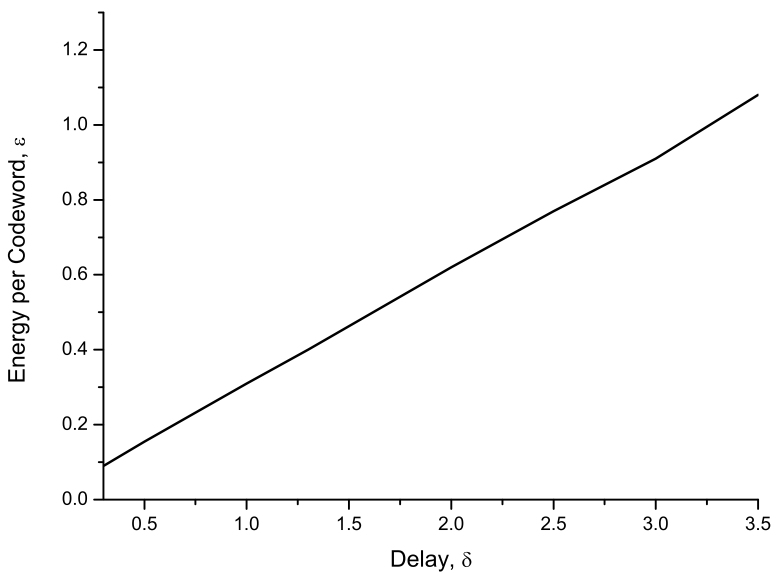
6.5 Simulation Results

The result is verified by simulation results as illustrated in Fig. 6-3. As claimed in the analytical evaluations, reliability can be increased by increasing Hamming distance of the channel code if node density is below a threshold, corresponding to $1/p$ number of neighboring nodes. This shows that, MEC with large delays can compensate the absence of a medium access control scheme up to nano-node density of $\rho_(max)$.

When M is constant, increasing code distance, d, increases the delay via codeword length according to (6.2). Since increasing d makes communication more reliable,



(a) Rate-delay for M = 16, p = 0.01



(b) energy-delay for M = 16, p = 0.01

Figure 6-4: Rate-delay and energy-delay for M = 16, p = 0.01

rate is expected to increase with delay. The variation of rate delay and energy with increasing Hamming distance is observed in Fig. 6-4. Convergence of rate-delay curve to $logM$ is expected, since

$$\lim_{d\to\infty} R = \lim_{d\to\infty} \xi_d logM = logM, \tag{6.20}$$

As expected code weight increases with d, average energy per codeword also increases. This result indicates that, larger delays via increasing Hamming distance, can make the communication more reliable for a maximum rate of $log(M)$.

When d is constant, increasing source cardinality, M, increases the delay via codeword length according to equation (6.2). The question that whether increasing M provides more reliable communication or not is more ambiguous. Under some simplifying assumptions, we can reach an approximate expression for collision probability, which can later be used to approximate correct decoding probability. Under the condition that d is even and $p_{max} < 0.5$, using the fact that $\eta_1 = 1/M$, for sufficiently large s, we have

$$p_x = 1 - (1 - \frac{p}{M})^s \approx 1 - e^{-1/M}, \tag{6.21}$$

This leads to,

$$p_c \approx \frac{M-1}{M}(1 - e^{-1/M}), \tag{6.22}$$

Since, $n \gg \lfloor \frac{d-1}{2} \rfloor$, we can write

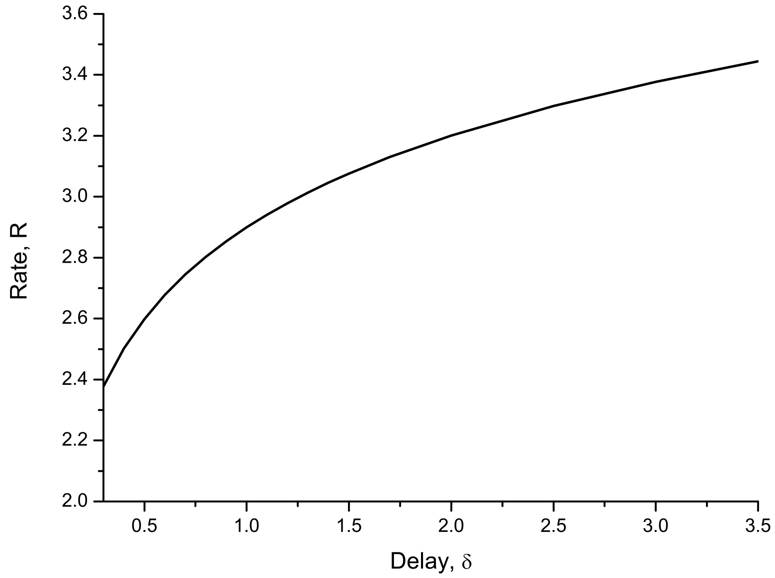
$$\xi_d \approx (1-p_c)^n \sum_{i=0}^{\lfloor \frac{d-1}{2} \rfloor} (\frac{np_c}{1-p_c})^i \frac{1}{i!} \tag{6.23}$$

$$\approx (e)^{-\frac{d}{2}} \sum_{i=0}^{\lfloor \frac{d-1}{2} \rfloor} [\frac{d}{2}(M-1)(e^{\frac{1}{M}} - 1)]^i \frac{1}{i!}, \tag{6.24}$$

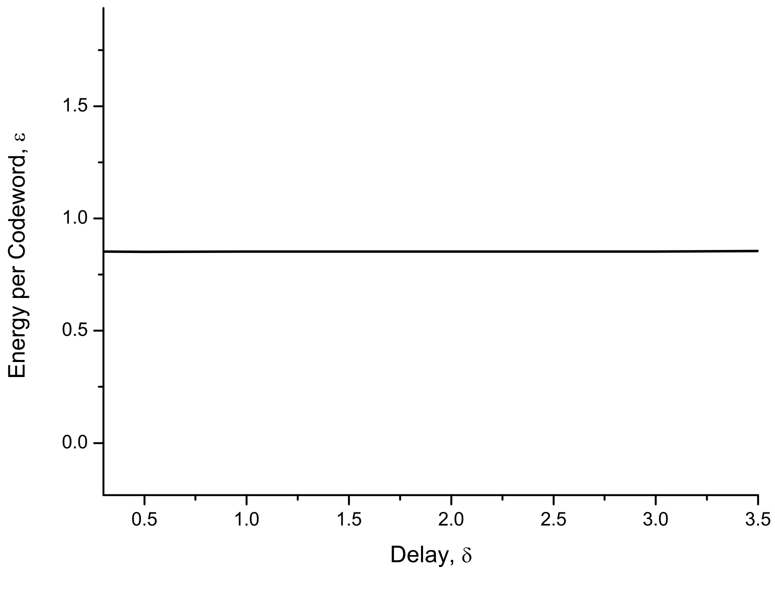
(6.23) is obtained using the expression in (6.22). In the limit,

$$\lim_{M\to\infty} \xi_d \approx (e)^{-\frac{d}{2}} \sum_{i=0}^{\lfloor \frac{d-1}{2} \rfloor} (\frac{d}{2})^i \frac{1}{i!} = \xi', \tag{6.25}$$

From (6.25), as M increases, ξ_d converges to a nonzero probability value. There-



(a) Rate-delay for d = 3, p = 0.01



(b) energy-delay for d = 3, p = 0.01

Figure 6-5: Rate-delay and energy-delay for d = 3, p = 0.01

fore, for very large M,

$$R \approx \xi' log M, \tag{6.26}$$

This result reveals that, by increasing the source set cardinality at the source nano-node, one can increase the communication rate with satisfying reliable communication with high probability, for large delays. The variation of rate delay and energy with increasing source set cardinality is observed in Fig. 6-5, agreeing with theoretical results. Average energy does not increase with delay, since $E(w)$ does not depend on M.

6.6 Summary

In this paper, limits and tradeoffs of BANN employing MEC are investigated. It is demonstrated that reliable communication, i.e., perfect codeword decoding, can be achieved using MEC in relay-based nanonetworks with a bounded number of interfering nano-nodes, without any medium access control. The exact expression for decoding probability is derived, and it is concluded that nano-node density ρ should be less than the inverse of node transmission probability $1/p$ to achieve reliable communication. Furthermore, rate-delay and energy-delay are analyzed for constant codebook size M with varying Hamming distance d and vice versa. The analysis reveals that for constant M, the average energy and rate increase with delay. However, for constant d, the energy dissipation remains constant as delay increases. Additionally, it is shown that increasing source set cardinality will lead to rates a constant multiple of $logM$ for BANN.

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Chapter 7

Conclusion

This chapter summarizes our contributions and points out future research directions.

7.1 Summary of the Thesis

This work focuses on energy efficiency management and data collection scheme for Body Area Nanonetworks (BANNs).The main contributions are summarized as follows.

- As an initial step towards this end, this paper focuses on a framework of energy efficiency data collection scheme for BANNs. The proposed architecture consists of inside-body network and outside external healthcare monitoring system. Inside-body network (composed of nano-nodes, nano-routers, and a nano-interface) is connected to the outside external healthcare monitoring system using nano-interface. This paper is concerned with the effective utilization of energy inside-body network, and proposes three types of scenarios.

- In the view of the aforementioned problems, we consider a simple scenario with only one nano-router, propose a lightweight data collection scheme in BANNs. First, a sleep/wake-up mechanism is introduced to avoid the unnecessary energy consumption when no external request comes. Then, with a careful consideration of both node available energy and transmission energy consumption, we design a new node selection strategy to further reduce the energy consumption in the data collection process. Finally, we conduct extensive simulations for both the proposed data collection scheme and the benchmark greedy scheme to illustrate the energy efficiency of our scheme as well as to discuss the impacts of network parameters on network performance.

- In the next place, We further propose a new energy efficient data collection scheme under a complex scenario with multiple nano-nodes and nano-routers in BANNs. With the scheme, we first categorize data as emergency data and normal data to fully consider the limited energy constraints. We then use this classification to generate distinct packets and assign priorities. In BANNs, the normal data is usually sent regularly, while the emergent data is sent immediately. Extensive simulations are also provided to validate energy efficiency of our scheme in comparison with other benchmark greedy scheme, and to illustrate impacts of network parameters on network performance.
- Finally, we propose a relay-based energy-efficient data collection scheme with minimum energy coding. Under the scheme, we derive maximum nano-node density for reliable communication in BANNs, and conduct density dependent reliability analysis. Both rate-energy and delay-energy tradeoffs are also investigated with constant codebook size and constant Hamming distance, respectively. We also provide extensive simulations to validate our scheme.

7.2 Future Works

We summarize the future interesting directions as follows.

- In this thesis, we consider some simple scenarios, where a single nano-router, multiple nano-routers and multiple nano-routers with nano-relay, which may cause a waste of the transmission opportunity if the relay node does not carry coded packet for the receiver. Therefore, one interesting future direction is to further explore the performance of BANNs under a more flexible scenario, where each relay node can select its receiver from the neighbor nodes for which it carries coded packets.

- This paper only considers the energy problem in the Body Area Nanoetworks, but also should consider the security and privacy issues.
- It is notable that our studies in this thesis focused on electromagnetic communication in the Body Area Nanoetworks. Another interesting direction is to further extend the developed molecular communication. It is also interesting to explore the network performance in our future research.

Bibliography

[1] I. F. Akyildiz, F. Brunetti, and C. Blázquez. Nanonetworks: a new communication paradigm. *Computer Networks*, 52(12):2260–2279, 2008.

[2] N. A. Ali and M. Abu-Elkheir. Internet of nano-things healthcare applications: Requirements, opportunities, and challenges. In *2015 IEEE 11th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Abu Dhabi, United Arab Emirates*, pages 9–14, 2015.

[3] I. F. Akyildiz and J. M. Jornet. The internet of nano-things. *IEEE Wireless Communications*, 17(6):58–63, 2010.

[4] M. Seyedi, B. Kibret, D. T. H. Lai, and M. Faulkner. A survey on intrabody communications for body area network applications. *IEEE Transactions on Biomedical Engineering*, 60(8):2067–2079, 2013.

[5] I. F. Akyildiz, M. Pierobon, S. Balasubramaniam, and Y. Koucheryavy. The internet of bio-nanothings. *IEEE Communications Magazine*, 53(3):32–40, 2015.

[6] B. Atakan, O. B. Akan, and S. Balasubramaniam. Body area nanonetworks with molecular communications in nanomedicine. *IEEE Communications Magazine*, 50(1):28–34, 2012.

[7] G. E. Santagati and T. Melodia. Opto-ultrasonic communications for wireless intra-body nanonetworks. *Nano Communication Networks*, 5(1):3–14, 2014.

[8] F. Dressler and S. Fischer. Connecting in-body nano communication with body area networks: Challenges and opportunities of the internet of nano things. *Nano Communication Networks*, 6(2):29–38, Jun 2015.

[9] Y. Moritani, S. Hiyama, and T. Suda. Molecular communication for health care applications. In *Fourth Annual IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOMW'06)*, pages 1–5, 2006.

[10] D. Malak and O.B. Akan. Molecular communication nanonetworks inside human body. *Nano Communication Networks*, 3(1):19–35, 2012.

[11] M. A. Hanson, H.C. Powell, A. T. Barthand, et al. Body area sensor networks: Challenges and opportunities. *Computer*, 42(1):58–65, 2009.

[12] R. M. Westervelt. Applied physics. graphene nanoelectronics. *Science*, 320(5874):324–325, Apr 2008.

[13] T. S. Rappaport. *Wireless communications - principles and practice*. Prentice Hall, 1996.

[14] I. F. Akyildiz and J. M. Jornet. Electromagnetic wireless nanosensor networks. *Nano Communication Networks*, 1(1):3–19, 2010.

[15] H. Yu, B. Ng, and W. K. G. Seah. Forwarding schemes for EM-based wireless nanosensor networks in the terahertz band. In *Proceedings of the Second Annual International Conference on Nanoscale Computing and Communication, NANOCOM 2015, Boston, USA*, pages 17:1–17:6, 2015.

[16] S. Misra, N. Islam, J. Mahapatro, and J. J. P. C. Rodrigues. Green wireless body area nanonetworks: Energy management and the game of survival. *IEEE Journal of Biomedical and Health Informatics*, 18(2):467–475, Mar 2014.

[17] M. Kocaoglu, D. Malak, and O. B. Akan. Fundamentals of green communications and computing: Modeling and simulation. *Computer*, 45(9):40–46, 2012.

[18] J. Suzuki, S. Balasubramaniam, S. Pautot, V. D. P. Meza, and Y. Koucheryavy. A service-oriented architecture for body area nanonetworks with neuron-based molecular communication. *Mobile Networks and Applications*, 19(6):707–717, 2014.

[19] M. Moore, A. Enomoto, T. Nakano, R. Egashira, T. Suda, A. Kayasuga, H. Kojima, H. Sakakibara, and K. Oiwa. A design of a molecular communication system for nanomachines using molecular motors. In *Fourth Annual IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOMW'06), Pisa, Italy*, pages 554–559, 2006.

[20] M. Meyyappan, Jing Li, Jun Li, and A. Cassell. Nanotechnology: An overview and integration with mems. In *19th IEEE International Conference on Micro Electro Mechanical Systems, Istanbul, Turkey*, pages 1–3, 2006.

[21] Y. J. Yun, C. S. Ah, S. Kim, W. S. Yun, B. C. Park, and D. H. Ha. Manipulation of freestanding au nanogears using an atomic force microscope. *Nanotechnology*, 18(50):505304, Nov 2007.

[22] V. Balzani, A. Credi, S. Silvi, and M. Venturi. Artificial nanomachines based on interlocked molecular species: Recent advances. *Chemical Society Reviews*, 35(11):1135–1149, Dec 2006.

[23] B. Behkam and M. Sitti. Bacterial flagella-based propulsion and on/off motion control of microscale objects. *Applied Physics Letters*, 90(2):1, Jan 2007.

[24] A. Cavalcanti, B. Shirinzadeh, R. A. Freitas, and T. Hogg. Nanorobot architecture for medical target identification. *Nanotechnology*, 19(1):015103, Jan 2008.

[25] L. Parcerisa and I. F. Akyildiz. Molecular communication options for long range nanonetworks. *Computer Networks*, 53(16):2753–2766, Nov 2009.

[26] A. Guney, B. Atakan, and O. B. Akan. Mobile ad hoc nanonetworks with collision-based molecular communication. *IEEE Transactions on Mobile Computing*, 11(3):353–366, March 2012.

[27] P. Lu, Z. Wu, and B. Liu. A vertical channel model of molecular communication and its test-bed. *EAI Endorsed Transactions on Pervasive Health and Technology*, 3(9):1–8, Mar 2017.

[28] C. Rutherglen and P. Burke. Nanoelectromagnetics: circuit and electromagnetic properties of carbon nanotubes. *Small*, 5(8):884–906, Apr 2009.

[29] J. M. Jornet and I. F. Akyildiz. Graphene-based nano-antennas for electromagnetic nanocommunications in the terahertz band. In *Proceedings of the Fourth European Conference on Antennas and Propagation, Barcelona, Spain*, pages 1–5, 2010.

[30] J. M. Jornet and I. F. Akyildiz. Channel capacity of electromagnetic nanonetworks in the terahertz band. In *Proceedings of IEEE International Conference on Communications, ICC 2010, Cape Town, South Africa*, pages 1–6, 2010.

[31] B. Atakan and O. B. Akan. Carbon nanotube sensor networks. *Proc of IEEE Nanocom, San Francisco, CA*, 2009.

[32] M. Chen, S. Gonzalez, A. Vasilakos, H. Cao, and V. C. Leung. Body area networks: A survey. *Mobile networks and applications*, 16(2):171–193, Apr 2011.

[33] S. Ullah, H. Higgins, B. Braem, B. Latret, C. Blondia, I. Moerman, S. Saleem, Z. Rahman, and K. Kwak. A comprehensive survey of wireless body area networks. *Journal of medical systems*, 36:1065–94, Aug 2010.

[34] A. Pantelopoulos and N. G. Bourbakis. A survey on wearable sensor-based systems for health monitoring and prognosis. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 40(1):1–12, Jan 2010.

[35] T. O'Donovan, J. O'Donoghue, C. Sreenan, D. Sammon, P. O'Reilly, and K. A. O'Connor. A context aware wireless body area network (ban). In *2009 3rd International Conference on Pervasive Computing Technologies for Healthcare, London, UK*, pages 1–8, 2009.

[36] M. R. Yuce. Implementation of wireless body area networks for healthcare systems. *Sensors and Actuators A Physical*, 162(1):116–129, Jul 2010.

[37] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, and A. Jamalipour. Wireless body area networks: A survey. *IEEE Communications Surveys Tutorials*, 16(3):1658–1686, Sep 2014.

[38] Ieee standard for local and metropolitan area networks - part 15.6: Wireless body area networks. *IEEE Std 802.15.6-2012*, Feb 2012.

[39] C. E. Koksal and E. Ekici. A nanoradio architecture for interacting nanonetworking tasks. *Nano Communication Networks*, 1(1):63–75, 2010.

[40] V. Loscrí, A. M. Vegni, and G. Fortino. On the interaction between a nanoparticulate system and the human body in body area nanonetworks. *Micromachines*, 6(9):1213–1235, 2015.

[41] R.A. Freitas. Nanotechnology, nanomedicine and nanosurgery. *International Journal of Surgery*, 3(4):243–246, Nov 2005.

[42] R. Z. Shafagh, A. Vastesson, W. Guo, W. Wijngaart, and T. Haraldsson. E-beam nanostructuring and direct click biofunctionalization of thiolcene resist. *ACS Nano*, 12(10):9940–9946, sep 2018.

[43] J. W. Yoo, D. J. Irvine, D. E. Discher, and S. Mitragotri. Bio-inspired, bioengineered and biomimetic drug delivery carriers. *Nature Reviews Drug Discovery*, 10(7):521, Jul 2011.

[44] G. V. Maltzahn, J.-H. Park, K. Y. Lin, N. Singh, C. Schwoppe, R. Mesters, W. E. Berdel, E. Ruoslahti, M. J. Sailor, and S. N. Bhatia. Nanoparticles that communicate in vivo to amplify tumour targeting. *Nature Materials*, 10(7):545–52, Jun 2011.

[45] W. Gao, R. Dong, S. Thamphiwatana, J. Li, W. Gao, L. Zhang, and J. Wang. Artificial micromotors in the mouse's stomach: a step toward in vivo use of synthetic motors. *Acs Nano*, 9(1):117–23, Jan 2015.

[46] S. Betal, A. K. Saha, E. Ortega, M. Dutta, A. K. Ramasubramanian, A. S. Bhalla, and R. Guo. Core-shell magnetoelectric nanorobot c a remotely controlled probe for targeted cell manipulation. *Scientific Reports*, 8(1):1755, Jan 2018.

[47] G. Piro, G. Boggia, and L. A. Grieco. On the design of an energy-harvesting protocol stack for body area nano-networks. *Nano Communication Networks*, 6(2):74–84, 2015.

[48] S. Abadal and I. F. Akyildiz. Automata modeling of quorum sensing for nanocommunication networks. *Nano Communication Networks*, 2(1):74–83, 2011.

[49] X. Li and B. Wei. Supercapacitors based on nanostructured carbon. *Nano Energy*, 2(2):159–173, 2012.

[50] J. Wang, J. Kim, L. Shu, Y. Niu, and S. Lee. A distance-based energy aware routing algorithm for wireless sensor networks. *Sensors*, 10(10):15–25, 2010.

[51] L. Wang, P. Wang, C. Yi, and Y. Li. Energy consumption optimization based on transmission distance for wireless on-body communication. In *Proceedings of the International Conference on Wireless Communications and Signal Processing, WCSP 2013, Hangzhou, China*, pages 1–6, 2013.

[52] O. Omeni, A. C. W. Wong, A. J. Burdett, and C. Toumazou. Energy efficient medium access protocol for wireless medical body area sensor networks. *IEEE Transactions on Biomedical Circuits and Systems*, 2(4):251–259, 2008.

[53] A. Rahim, N. Javaid, M. Aslam, Z. Rahman, U. Qasim, and Z. A. Khan. A comprehensive survey of mac protocols for wireless body area networks. In *2012 Seventh International Conference on Broadband, Wireless Computing, Communication and Applications, Victoria, Canada*, pages 434–439, 2012.

[54] M. M. Alam, O. Berder, D. Ménard, and O. Sentieys. Tad-mac: Traffic-aware dynamic MAC protocol for wireless body area sensor networks. *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, 2(1):109–119, 2012.

[55] K. Chi, Y. Zhu, X. Jiang, and V. C. M. Leung. Energy-efficient prefix-free codes for wireless nano-sensor networks using ook modulation. *IEEE Transactions on Wireless Communications*, 13(5):2670–2682, May 2014.

[56] M. Magno, S. Marinkovic, D. Brunelli, L. Benini, and E. Popovici. Combined methods to extend the lifetime of power hungry wsn with multimodal sensors and nanopower wakeups. In *2012 8th International Wireless Communications and Mobile Computing Conference (IWCMC),Limassol, Cyprus*, pages 112–117, 2012.

[57] F. Casamassima, M. Magno, E. Farella, and L. Benini. Context aware power management enhanced by radio wake up in body area networks.

In *2015 IEEE 13th International Conference on Embedded and Ubiquitous Computing, Porto, Portugal*, pages 76–82, 2015.

[58] S. Mohrehkesh and M. C. Weigle. Optimizing energy consumption in terahertz band nanonetworks. *IEEE Journal on Selected Areas in Communications*, 32(12):2432–2441, Dec 2014.

[59] H. Kroll, M. Korb, B. Weber, S. Willi, and Q. Huang. Maximum-likelihood detection for energy-efficient timing acquisition in nb-iot. In *2017 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), San Francisco, USA*, pages 1–5, 2017.

[60] J. Xiong and H. Li. Receiver design for binary timing-based molecular communication. In *2016 8th International Conference on Wireless Communications Signal Processing (WCSP), Yangzhou, China*, pages 1–6, 2016.

[61] J. M. Jornet and I. F. Akyildiz. Joint energy harvesting and communication analysis for perpetual wireless nanosensor networks in the terahertz band. *IEEE Transactions on Nanotechnology*, 11(3):570–580, 2012.

[62] K. Yang, A. Pellegrini, M. O. Munoz, A. Brizzi, A. Alomainy, and Y. Hao. Numerical analysis and characterization of thz propagation channel for body-centric nano-communications. *IEEE Transactions on Terahertz Science and Technology*, 5(3):419–426, May 2015.

[63] I. Llatser, A. Cabellos-Aparicio, E. Alarcn, J. M. Jornet, A. Mestres, H. Lee, and J. Sol-Pareta. Scalability of the channel capacity in graphene-enabled wireless communications to the nanoscale. *IEEE Transactions on Communications*, 63(1):324–333, Jan 2015.

[64] A. K. Vavouris, F. D. Dervisi, V. K. Papanikolaou, and G. K. Karagiannidis. An energy efficient modulation scheme for body-centric nano-communications in the thz band. In *2018 7th International Conference on Modern Circuits and Systems Technologies (MOCAST), Thessaloniki, Greece*, pages 1–4, 2018.

[65] M. Kocaoglu and D. Malak. On the node density limits and rate-delay-energy tradeoffs in ad hoc nanonetworks with minimum energy coding. In *2012 IEEE International Conference on Communications (ICC), Ottawa, Canada*, pages 6157–6161, 2012.

[66] B. Atakan and O. B. Akan. Carbon nanotube-based nanoscale ad hoc networks. *IEEE Communications Magazine*, 48(6):129–135, June 2010.

[67] J. M. Jornet and I. F. Akyildiz. Low-weight channel coding for interference mitigation in electromagnetic nanonetworks in the terahertz band. In *2011 IEEE International Conference on Communications (ICC)*, pages 1–6, 2011.

[68] M. Kocaoglu and O. B. Akan. Minimum energy coding for wireless nanosensor networks. In *2012 Proceedings IEEE INFOCOM, Orlando, USA*, pages 2826–2830, 2012.

[69] B. Tavli and W. B. Heinzelman. Energy-efficient real-time multicast routing in mobile ad hoc networks. *IEEE Transactions On Computers*, 60(5):707–722, May 2011.

[70] M. Pierobon, J. M. Jornet, N. Akkari, S. Almasri, and I. F. Akyildiz. A routing framework for energy harvesting wireless nanosensor networks in the terahertz band. *Wireless Networks*, 20(5):1169–1183, 2014.

[71] S. Canovas-Carrasco, A. J. Garcia-Sanchez, F. Garcia-Sanchez, and J. Garcia-Haro. Conceptual design of a nano-networking device:. *Sensors (Basel, Switzerland)*, 16(12), Dec 2016.

[72] S. Canovas-Carrasco and A. J. Garcia-Sanchez andJ. Garcia-Haro. A nanoscale communication network scheme and energy model for a human hand scenario. *Nano Communication Networks*, 15:17–27, Mar 2018.

[73] N. Rodriguez, S. Cristoloveanu, and F. Gamiz. A-ram: Novel capacitor-less dram memory. In *2009 IEEE International SOI Conference, Foster City, USA*, pages 1–2, 2009.

[74] P. M. Kosaka, V. Pini, J. J. Ruz, R. A. Silva, M. U. Gonzlez, D. Ramos, M. Calleja, and J. Tamayo. Detection of cancer biomarkers in serum using a hybrid mechanical and optoplasmonic nanosensor. *Nature Nanotechnology*, 9(12):1047–1053, Nov 2014.

[75] M. S. Mannoor, H. Tao, J. D. Clayton, A. Sengupta, D. L. Kaplan, R. R. Naik, N. Verma, F. G. Omenetto, and M. C. McAlpine. Graphene-based wireless bacteria detection on tooth enamel. *Nature Communications*, 3(3):763, Mar 2012.

[76] S. Xu, Y. Qin, C. Xu, Y. Wei, R. Yang, and Z. Wang. Self-powered nanowire devices. *Nature Nanotechnology*, 5(5):366–373, Mar 2010.

[77] M. Donohoe, S. Balasubramaniam, B. Jennings, and J. M. Jornet. Powering in-body nanosensors with ultrasounds. *IEEE Transactions on Nanotechnology*, 15(2):151–154, March 2016.

[78] G. Piro, P. Bia, G. Boggia, D. Caratelli, L. A. Grieco, and L. Mescia. Terahertz electromagnetic field propagation in human tissues: A study on communication capabilities. *Nano Communication Networks*, 10, Dec 2016.

[79] E. Berry, A. J. Fitzgerald, N. N. Zinov'Ev, G. C. Walker, S. Homervanniasinkam, C. D. Sudworth, R. E. Miles, J. M. Chamberlain, and M. A. Smith. Optical properties of tissue measured using terahertz-pulsed imaging. *Proceedings of SPIE: Physics of Medical Imaging*, 5030:459–470, 2003.

[80] J. M. Jornet and I. F. Akyildiz. Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band. *IEEE Transactions on Wireless Communications*, 10(10):3211–3221, 2011.

[81] J. M. Jornet and I. F. Akyildiz. Information capacity of pulse-based wireless nanosensor networks. In *Proceedings of the 8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, SECON 2011, Salt Lake City, USA*, pages 80–88, 2011.

[82] J. Xu, K. W. Plaxco, and S. J. Allen. Absorption spectra of liquid water and aqueous buffers between 0.3 and 3.72 THz. *Journal of Chemical Physics*, 124(3):36101–36101, 2006.

[83] L. Huang, W. Wang, and S. Shen. Energy-efficient coding for electromagnetic nanonetworks in the terahertz band. *Ad Hoc Networks*, 40:15–25, Apr 2016.

[84] E. Gul, B. Atakan, and O. B. Akan. Nanons: A nanoscale network simulator framework for molecular communications. *Nano Communication Networks*, 1(2):138–156, 2010.

[85] B. Liu, Y. Zhang, X. Jiang, and Z. Wu. An energy-efficient data collection scheme in body area nanonetworks. In *2015 Third International Symposium on Computing and Networking (CANDAR), Sapporo, Japan*, pages 240–245, 2015.

[86] Y. Wang, Q. Wu, X. He, S. Zhang, and L. Zhuang. Terahertz radiation from armchair carbon nanotube dipole antenna. *Chinese Phys. B*, 18(5):1801–1806, 2009.

[87] Y. Luo, J. Zhang, and K. B. Letaief. Optimal scheduling and power allocation for two-hop energy harvesting communication systems. *IEEE Transactions on Wireless Communications*, 12(9):4729–4741, September 2013.

Publications

Journal Articles

[1] **Bo Liu**, Jia Liu, Zhenqiang Wu and Xiaohong Jiang. On the Design of an Energy-efficient Data Collection Scheme for Body Area Nanonetworks. *International Journal of Wireless and Mobile Networks*, 9(3): 15–28, June 2017.

[2] Pengfei Lu, Zhenqiang Wu and **Bo Liu**. A Vertical Channel Model of Molecular Communication and Its Test-bed. *EAI Endorsed Transactions on Pervasive Health and Technology*, 3(9): 1–8, March 2017.

Conference Papers

[3] **Bo Liu**, Yuanyu Zhang, Xiaohong Jiang and Zhenqiang Wu. An Energy-Efficient Data Collection Scheme in Body Area Nanonetworks. In *Proc. CANDAR*, 2015.

[4] **Bo Liu**, Pengfei Lu, Xuanwen Hao, Xiaohong Jiang and Zhenqiang Wu. Data Collection Scheme Based on Wake-up in Body Area Nanonetworks. In *Proc. NaNA*, 2016.

[5] Xinlei Wang, Zhenqiang Wu, Jiawang Chen, Xuanwen Hao and **Bo Liu**. Reliability Analysis of Molecular Communication Based on Drift Diffusion. In *Proc. NaNA*, 2017.