M.Sc. Engg. Thesis

Network-level Perfromance Evaluation and Enhancement through Multi-layer Modifications for Ad hoc Wireless Nanosensor Networks

by

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Dedicated to my loving parents

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Candidate's Declaration

This is hereby declared that the work titled "Network-level Perfromance Evaluation and Enhancement through Multi-layer Modifications for Ad hoc Wireless Nanosensor Networks", is the outcome of research carried out by me under the supervision of Dr. A. B. M. Alim Al Islam, in the Department of Computer Science & Engineering, Bangladesh University of Engineering & Technology, Dhaka 1000. It is also declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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Abstract

Researchers consider wireless nanosensor networks (WNSNs), operating over the Terahertz (THz) band, as a revolutionary emerging network paradigm from the point of its diversified applications and contributions to the humanity. Communication over such networks is anticipated to experience different challenges due to having unique characteristics such as nano-antenna behavior, small transmission range, limited operating capabilities, etc. Existing research in this field is still in elementary stage and performance enhancement via designing protocol suit represents a potential issue to address for this field. However, most of the studies in the literature mainly focus on lower layers, i.e., Physical and MAC layer protocols leaving upper layers such as Network layer and Transport layer protocols still unexplored.

Additionally, impact of utilizing classical routing protocols such as AODV, DSDV, and DSR in ad hoc WNSNs is still to be explored in the literature. Therefore, in this study, we explore network-level performance of WNSNs for different network settings. First, we develop a system model for WNSNs considering real nano-antenna behavior along with THz communication. Subsequently, we enable these aspects in the network simulator `ns-2` through performing necessary modifications in the simulator. Afterwards, we analyze the network-level performance of WNSNs through adopting classical ad hoc routing protocols such as AODV, DSDV, and DSR for different transmission ranges, different number of nanosensors, and different MAC alternatives. Next, utilizing results of the performance analysis, we propose a hierarchical AODV routing protocol for Network layer and an acknowledgement-based UDP protocol for Transport layer with a goal of enhancing network-level performance in ad hoc WNSNs. Finally, we evaluate performance of our proposed protocols and compare with existing protocols in `ns-2` based on the performance metrics such as network throughput, end-to-end delay, total energy consumption, energy consumption per bit, packet delivery ratio, and packet drop ratio.

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Chapter 1

Introduction

The recent boost in nanotechnology fosters extension of control and networking to nano scale by deployment of nanosensors having a size of one to few hundred nanometers. Being equipped with a nano-antenna, a memory, a CPU, and a power supply, such nanosenors are enabled to perform simple operations and wireless communication in short distances. Fig. 1.1 demonstrates general structure of a nano device. Nanosensors are very small in size (Fig. 1.2) and able to perform simple operations such as storing data, logical and computing operations, actuation, and controlling tasks. Wireless communication among such nanosensors bolsters emergence of a new paradigm called wireless nanosensor networks (WNSNs). Furthermore, the recent introduction of graphene based nano-antennas enhances the capability of wireless communication in WNSNs exploiting the most promising operating spectrum over terahertz band [3]. Therefore, WNSNs are envisioned to have promising applications [4, 5] in near future in diversified fields such as biomedical devices, environment science, industrial development,

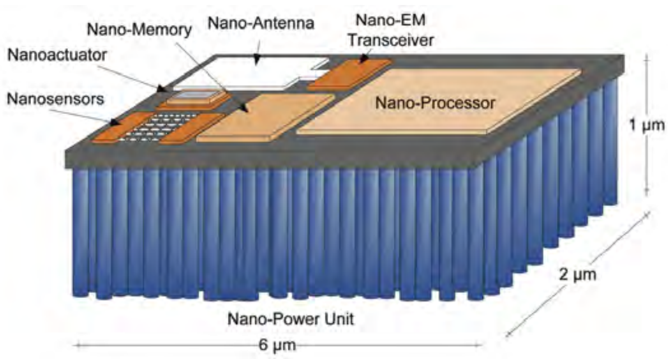


Figure 1.1: A typical nano device

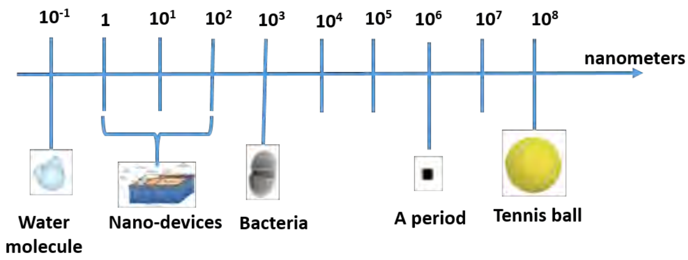
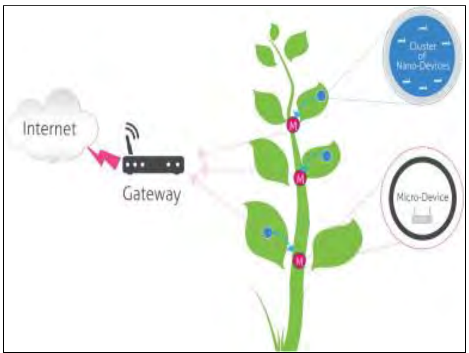


Figure 1.2: Comparison of size of nano device

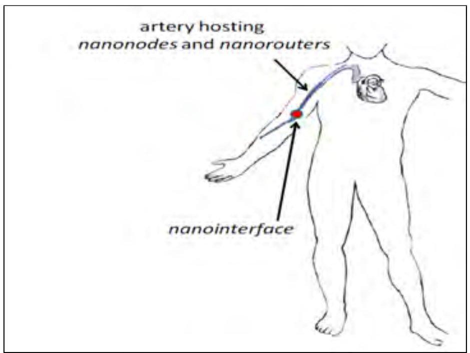
food science, etc.

1.1 Existing Proposed Applications of Nanonetworks

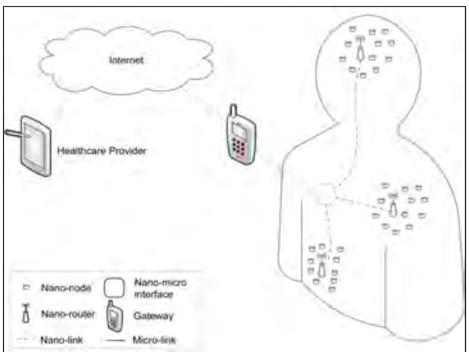
There exist some classical applications of nanonetworks. Figure 1.3 shows some applications that has been proposed. Nano devices can be utilized for environmental monitoring such as observing the condition of leaves in trees (Fig. 1.3(a)). Besides, the use of nanonetworks in healthcare applications has been investigated in [8, 7] which is demonstrated in Fig. 1.3(b),



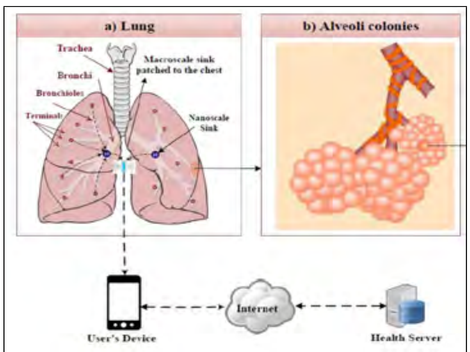
(a) Environmental monitoring [6]



(b) Drug delivery [1]



(c) Health status monitoring [6]



(d) Monitoring of an organ [7]

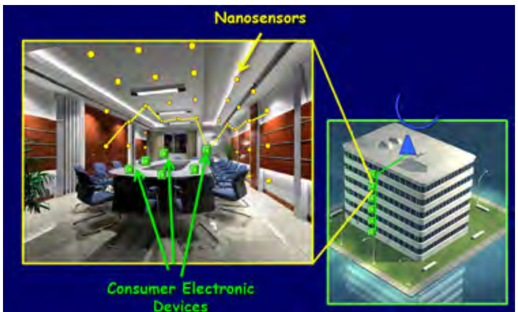
Figure 1.3: Claasical applications of nanonetworks

1.3(c), and 1.3(d). In healthcare applications, nano devices can be used for blood pressure monitoring, measurement of heart bit rate (Fig. 1.3(c)), drug delivery(Fig. 1.3(b)), and pulse oximetry etc. Fig. 1.3(d) shows that nano devices can also be used for monitoring of human lung cells. However, most of these existing proposed applications consider molecular communications among nano devices for biomedical applications. In molecular communication, the molecules are formulated as information carriers in human body. The information can be protein, RNA, etc.

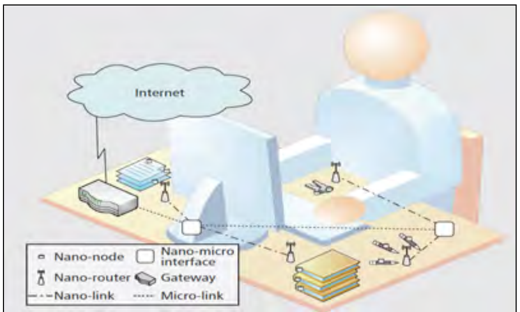
1.2 Potential Future Applications of Nanonetworks

(a) Smart office


(b) Smart cloth store



(c) Room monitoring



(d) Locating office belongings


(e) File store

Figure 1.4: Potential future applications of WNSNs

Most of nanonetworks applications focus on inner-body applications. There exist another way of communication among nano devices which is electromagnetic communication (EM). We are focusing on the outer-body applications using electromagnetic communication. However, electromagnetic waves are harmful to living tissue [9]. Besides, radiation from electromagnetic communication (EM) can harm human body. The EM waves have to pass through tissues and other fluids such as blood cells in human body. To propagate in human body, EM waves require more power to pass through living tissues and blood cells. Higher power can cause more harm in human body. Therefore, electromagnetic waves are not suitable for communication in many cases pertinent to inner-body applications. However, EM communication can be a potential solution for outer-body applications in nano-scale.

We are considering outer body applications of nanonetworks such as smart office, smart book store, smart cloth store, shopping mall, luggage in airport, locating office belongings, etc. These potential future applications of nanonetwworks using EM communication is demonstrated in Fig. 1.4 such as smart office (Fig. 1.4(a)), smart cloth store (Fig. 1.4(b)), book store, etc. Room, and office monitoring to detect unusual chemical substances are also important applications of nanonetworks. Nanonetworks can also be used for locationg office belongings and files (Fig. 1.4(e)). Considering these potential future applications of WNSNs, there is a need to analyze the network behavior of WNSNs. Integrated nano devices have not been built yet to the best of our knowledge, thus it offers a wide variteies of research studies pertaining design of nano devices as well as development of WNSNs consisting of nano devices.

The area of nanonetworks is still under research. There exist another provision for small range communication which is RFID. The main difference between RFID and nano device is the size. The size of nano devices is very small (in nano-scale). On the other hand, the size of RFID is in centimetres or milimeters. Another difference is that multi-hop routing can be enabled in nano devices, however multi-hop routing can not be enabled in RFIDs. Here, the RFID tags only response to reader. The frequency band for nano devices is in Terahertz band whereas for RFIDs, it is in Megahertz band.

As we are considering some applications such as smart cloth store, smart book store, shopping mall, and smart office, the size of the devices is a major issue while considering these applications. For smart office, shopping mall, some objects or things can be very small such as pen, pencils, etc. Therefore, nano devices can be easily attached to these things as the size of nano devices is in nano-scale. For very small size belongings, RFID may not be a feasible solution. Here, the necessity of using nano devices comes to play.

Another important concern is multi-hop routing. RFID does not support multi-hop routing. Multi-hop routing can be enabled in nano devices. When the number of things is huge such as clothes in cloth store, piles of file in file store, books in book store, if we use RFID, then we have to move each cloth bundle, book, or file to RFID reader. It may not be a feasible solution for these type of applications to move each and every object to detect the object. Therefore, if we can enable a network to locate these types of objects without moving them, it will offer a easy and flexible solution for these types of applications. Hence, nanonetworks can be a potential and effective solution for these kinds of applications.

The cost of nano devices is another major concern. However, we are considering utilization of nano devices for such cases where the number of objects of things is massive. When we will use the nano devices in mass-scale, then we can estimate that the overall cost will be lower. When the technology will become matured, the cost will be reduced. And the applications of nanonetworks will offer an easy and effective solution for many scenarios.

1.3 Limitations of The Existing Research Studies

However, communication in WNSNs is expected to experience different challenges, owing to limitations in capabilities of the nanosensors such as limited transmission range, less processing power, small memory, scarcity of energy, etc. The key features of nano devices can be summarized as follows:

- Nano devices radiate over terahertz band using nano antennas.
- This devices have very low power and limited operating capabilities owing to their tiny size.
- The bit rates of communication among nano devices are extremely high (terabit/s)
- Such devices have very small transmission ranges (tens of millimeters).

These limitations of nanosensors introduce mammoth challenges in designing different protocols for WNSNs [10]. One of the key constraints in designing the protocols is to maintain simplicity without compromising lifetime and connectivity of the WNSNs. However, most of the existing studies mainly focus on designing protocols for Physical and MAC layers, where the main focus remains limited to node-level energy efficiency [11, 12, 13, 14]. Besides, most of the proposed studies consider biomedical applications using molecular communication. Overall analysis on network behavior of WNSNs have been explored very little in the literature. The research on developing Network layer and Transport layer protocols for WNSNs is still in an incipient stage. Therefore, in this work, we focus on enhancing the performance of WNSNs exploiting multi-layer, i.e., Network and Transport layers, improvements.

The ability of WNSNs to be self-organized and re-configurable evolves WNSNs to the direction of ad-hoc networks. Therefore, it is interesting to explore how classical ad-hoc routing protocols perform in WNSNs. However, such exploration of performances of the classical routing protocols in WNSNs is yet to be explored in the literature. Therefore, in this study, we first analyze the performances of WNSNs for different classical ad-hoc routing protocols such as AODV, DSDV, and DSR. Our exploration reveals the superiority of AODV over the other two state-of-the-art protocols.

There exists a few studies on designing routing protocols for WNSNs in the literature [15]. Most of the existing protocols are flood-based, which results in redundancy and collisions. However, WNSNs have severe restrictions on available power supply. Hence, to boost performance of the networks sustaining the power restriction, a data routing protocol should keep redundant transmissions as low as possible. Therefore, in our work, we propose a customized hierarchical routing protocol based on AODV ensuring energy efficacy through reducing the number of transmissions of control packets. Furthermore, to boost up the performance enhancement further, we also propose a modification in the Transport layer through regulating flow in case of UDP.

Note that many forms of hierarchical structure have been proposed for ad-hoc networks and wireless sensor networks (WSNs) [16], [17]. However, owing to some special features of nano devices, determining the impact of hierarchical structure in WNSNs needs special care for guaranteeing improved performance using it. Hence, in this study, we focus on designing a customized hierarchial form of AODV routing protocol for WNSNs. Besides, several existing ACK-based approaches [18] exist for ad-hoc networks, even though determining the effect of ACK-based approach in nanonetwork is yet another aspect worth of investigating owing to the specialized features. Additionally, performance evaluation of WNSNs after adopting such customizations in Network and Transport layers is yet to be explored in the literature. Therefore, we conduct simulation to recognize the behavior of WNSNs through combining both our customizations made in these two layers.

1.4 Objectives of This Thesis

We identify the following objectives for this thesis:

- Integrate specialized behavior of graphene-based nano-antennas in `ns-2`.
- Analyze network-level performance of ad hoc WNSNs through adopting classical MAC, Network, and Transport layer protocols.
- Propose new protocols for Network layer and Transport layer for network-level performance enhancement in ad hoc WNSNs.
- Evaluate the performance of the proposed protocols using the network simulator `ns-2`.

1.5 Our Contributions

Based on our work, we make the following set of contributions:

- We develop a system model for WNSNs and analyze the performance of WNSNs in `ns-2` after performing necessary modifications in the simulator.
- Next, we use classical ad-hoc routing protocols such as AODV, DSDV, and DSR for different transmission ranges, different number of nanosensors, and different MAC alternatives. Our exploration reveals superiority of AODV over the other routing protocols.
- Utilizing the results of our analysis, we propose a hierarchical AODV routing protocol, which reduces transmission of control packets and thus enhances energy efficiency.

- We modify the Transport layer and propose an acknowledgement-based UDP protocol to further enhance the performance of WNSNs.
- Finally, we evaluate efficacy and efficiency of our proposed protocols for different performance metrics such as throughput, end-to-end delay, energy consumption, energy consumption per bit, delivery ratio, and packet drop, using rigorous `ns-2` simulation. Our evaluation reveals a number of novel findings pertinent to multi-layer performance enhancement in WNSNs.

1.6 Outline of Our Thesis

The rest of the book is organized in the following way. In Chapter 2, we will show the background and related research studies. After that in Chapter 3, we will discuss about the system model of wireless nanosensor networks. In Chapter 4, we discuss the methodology that we propose to improve network-level performance of WNSN. In the later chapter, we will show the performance evaluation of our proposed methodology. After that in Chapter 6, we willl have a short conclusion including the future possible research directions.

Chapter 2

Related Work

The concepts in nanotechnology was first mentioned by the 1965 nobel laureate physicist Richard Feynman in his famous speech entitled "There's Plenty of Room at the Bottom" in December 1959. The main notion of his speech was about the field of miniaturization or reducing the size of a device and how he believed humans would devise increasingly tinier and powerful devices in the future. The term "nanotechnology" was first introduced by [19] 15 years later as: "Nanotechnology mainly consists of the processing of, separation, consolidation, and deformation of materials by one atom or by one molecule". In the 1980s, the basic concept of this definition was revealed in much more depth by [20] who took the Feynman idea of a billion tiny factories and added the idea that they could replicate themselves, through computer control instead of control by a human operator. Activity surrounding nanotechnology began to slowly increase and the developments really started to accelerate in the early 2000s.

Nanotechnology enables the miniaturization and fabrication of devices in a scale ranging from one to few hundred nanometers. At this scale, a nano-machine can be considered as the most basic functional unit. Nano-machines are tiny components which are able to perform very simple computation, sensing and/or actuation tasks. Nano-machines can be further used as building blocks for the development of more complex systems such as nano-robots and computing devices such as nano-processors, nano-memory or nano-clocks.

There exist four types of communication paradigm for nanonetworks namely nanomechanical, acoustic, electromagnetic, and molecular communication. Among them, molecular communication and wireless electromagnetic (EM) communication has recently captured interest of research community for their multi-objective applications in many fields. The molecular or bio-inspired communication relies on biology as a source of inspiration and exploits biological molecules as information carriers. For example, the information is encoded on several biological molecules (e.g. RNA), which are diffused to the environment [21, 22]. Research efforts pertaining molecular communication are primarily focused on physical layer, MAC layer, and network layer issues in communication. One of the most common issues in the Physical layer is the propagation of signals in various media and environments. Hence, existing studies mainly focus on designing different propagation models such as random walk model [23], random walk models with drift [24, 25], diffusion-based models [26], diffusion-reaction based models [27], active transport models [28], and collision-based model [29] for molecular communication. Furthermore, existing studies using molecular communication focus on other issues of physical layer such as signal modulation [30], signal amplification [31], and channel capacity [32]. Moreover, there exists some research studies in the literature focusing diverse issues of link layer such as error handling [33, 34], addressing [35], and synchronization [36]. The authors in [37, 38] explore the development of routing protocol for molecular communication.

The wireless communication in nanonetworks is based on electromagnetic (EM) waves. However, the research in this field is still in rudimentary stage and thus delineates scopes for exploration of protocol stack, network architectures, and channel access procedure pertinent to diversified applications of WNSNs. Furthermore, most of the existing research efforts have focused deployment of Physical and MAC layer protocol, where the main intention lied on ensuring energy efficiency.

2.1 Existing Studies on Channel Modeling

Existing studies at Physical layer of WNSNs mainly focus on channel models and designing of nano-antenna imposing the capability to operate in terahertz band or in VHF band [12, 13, 23, 39, 40, 41, 42]. In [39], neuro-spike communication of molecular communications has been considered. Here, an interference model for synaptic channels with particular focus on InterSymbol Interference (ISI) and Single-Input Single-Output (SISO) channel is proposed. The authors here have investigated the overlapping between the two consecutively signals which are sent from a presynaptic terminal to a postsynaptic terminal and their interferences.

Additionally, important metrics of synaptic communication channel pertaining the ISI are also analyzed. The relationship between channel rate region and ISI is also explored.

The study presented in [40] investigate the state of the art in molecular electronics considering Terahertz Band (0.1-10.0 THz) for electromagnetic (EM) communication among nano-devices. Here, a new propagation model for EM communications in the Terahertz Band has been developed based on radiactive transfer theory and in light of molecular absorption. This model considers the total path loss and the molecular absorption noise that a wave in the Terahertz Band suffers when propagating over very short distances. Besides, the channel capacity of the Terahertz Band has been analyzed by using this model for different power allocation schemes, including a scheme based on the transmission of femtosecond-long pulses. In [41], the authors introduce the equivalent discrete-time channel model (EDTCM) to the area of diffusion-based molecular communication (DBMC). Here, the main focus is on an absorbing receiver, which is based on the first passage time concept. The EDTCM improves the accessibility of DBMC and supports the adaptation of classical wireless communication algorithms to the area of DBMC. Besides, for the exact EDTCM, three approximations based on binomial, Gaussian, and Poisson approximation are proposed and analyzed in order to reduce computational complexity. In addition, the Bahl-Cocke-Jelinek-Raviv (BCJR) algorithm is utilized for studying all four channel models.

The authors in [42] characterize the 'channel quantum response (CQR)' or equivalently the 'throughput response' of bio-inspired nanonetworks with an analytical approach. The approach is based on the spatial and temporal distribution of received concentration of the information molecules in a given propagation medium. They consider the molecular channel as particle propagation. The CQR i.e. the throughput response and its characteristics have been used in order to investigate the molecular channel behavior of nanonetworks. The work [23] analyzes the capacity of a molecular communication channel in a one-dimensional environment. Here, information is represented with molecules that are released by a transmitter nanomachine, propagate via Brownian motion, degrade over time, and stochastically reach the receiver nanomachine. The channel is modeled as a time slotted binary channel, and two modulation schemes are proposed namely a naive modulation scheme and an extended modulation scheme with a redundant number of molecules.

2.2 Existing Studies on Physical and MAC Layers

The study presented in [11] propose a new Physical layer Aware MAC protocol (PHLAME) for nanonetworks using EM communication in the Terahertz Band. This protocol utilizes a pulse-based communication scheme and a low-weight channel coding schemes for nanonetworks . In PHLAME, the transmitting and receiving nano devices jointly select the optimal communication scheme parameters and the channel coding scheme with a view to maximizing the probability of successfully decoding the received information while minimizing the generated multi-user interference. The authors in [14] propose a hierarchical network architecture, which integrates a BANNET (body area nanonetworks) and a macro-scale health-care monitoring system. They also propose two different energy-harvesting protocol stacks that regulate the communication among nano-devices during the execution of advanced nano-medical applications.

Moreover, the authors in [13] explore modulation and encoding schemes for nanosensor networks. Here, they propose the utilization of low-weight channel codes to mitigate the interference in pulse-based electromagnetic nanonetworks in the Terahertz band. Besides, the impulsive interference has been statistically modeled which is generated by a Poisson field of nanomachines that operate under a new pulse-based communication scheme named TSOOK (Time Spread On-Off Keying), and provide a closed-loop expression for the probability density function of the interference. The impact of the code weight on the total interference power and the information rate is analytically and numerically evaluated. Finally, this paper reveals that using low-weight channel codes, the overall interference can be reduced while keeping constant or even increasing the achievable information rate in an interference limited scenario.

At MAC layer, a Receiver Initiated Harvesting-aware MAC protocol is introduced in [43]. In RIH-MAC, receiver-initiated protocol has been proposed which takes into account the energy harvesting properties of nanonodes, where they may form a centralized or distributed network. The scalability with the increase in the number of nanonodes is also considered. This protocol is suitable to be deployed in a large number of nanonetwork applications, where delay and packet loss are not mandatory QoS requirements. Moreover, here, a cluster-based communication is considered among the nanosensors. Another harvesting-aware MAC protocol is introduced in [44] which utilizes a hierarchical cluster based architecture where all nanonodes communicate directly with the more powerful nanocontroller in one hop. Here, energy and spectrum-aware MAC protocols for WNSNs has been proposed which consider throughput and lifetime optimal channel access by jointly optimizing the energy harvesting and consumption processes. A system design parameter, namely, the critical packet transmission ratio (CTR) has been formulated, which is the maximum allowable ratio between the transmission time and the energy harvesting time, below which the nanosensor node can harvest more energy than the consumed one. Based on the CTR, a novel symbol compression scheduling algorithm is introduced using pulse-based physical layer technique. The symbol-compression algorithm uses the flexibility of the inter-symbol spacing of the pulse-based physical layer. This enables multiple nanosensors to transmit their packets concurrently without inducing any collisions. Besides, a packet-level timeline scheduling algorithm is proposed, which relies on a theoretical bandwidth adaptive capacity-optimal physical layer with a goal of achieving the balanced single-user throughput with the infinite network lifetime.

2.3 Existing Studies on Network Layer

At Network layer, a flood-based lightweight routing protocol is introduced in [45]. Here, an analytical model for the energy harvesting process of a nano-device is developed which is powered by a piezoelectric nano-generator. This model takes into account the energy consumption processes for communication among nano devices in the Terahertz Band. The variation in nano device energy and their corelation with the whole network traffic is modeled here. A mathematical framework to analyze the impact of several network metrics such as end-to-end packet delivery probability, the end-to-end delay, and the throughput is developed. However, this protocol suffers from redundancy and collisions, which degrades the performance of WNSNs with respect to energy consumption.

Besides, in [46], a joint coordinate and routing system (CORONA) for nanonetworks has been proposed. The joint coordinate and routing system here is considered to be deployed on a two-dimensional ad hoc nanonetwork. At setup phase, user-selected nodes are used as anchor-points. Then, all nodes compute their distances in number of hops from these anchors by utilizing geolocation. At operation phase, the routing is enabled by selecting the appropriate subset of anchors which are selected by the sender of a packet. Here, the rate of packet retransmission and packet loss rate are reduced. However, routing through fixed coordinate-based anchor nodes faces difficulty when any of the anchor nodes does not work properly.

In [1], the authors introduce an open source tool modeling WNSNs within the NS-3 simulator namely Nano-Sim. Here, they analyze and evaluate complete performance of a WNSN operating in a health-monitoring system. A new flooding routing algorithm and a more efficient MAC protocol are proposed focusing on a WNSN operating in a health monitoring scenario. The network behavior of WNSN is investigated to analyze the impact of the density of nodes, the transmission range of nanomachines, and the adoption of specific combinations of routing and MAC strategies. Another approach namely Dynamic Infrastructure (DIF) [15, 47] has been introduced to reduce transmissions without compromising the high network coverage. The key idea in DIF is that only nodes with good reception quality can act as retransmitters, while the remaining nodes revert to receiving-only mode. While the DIF approach ensures energy efficiency, as in the flood approach, every single node in the topology overhears transmitted packets in the network even when it is not necessary. Here, overall packet transmission is also diminished.

However, the exploitation of existing ad-hoc routing protocols for nanonetworks is yet to be explored. Moreover, designing WNSNs specific protocols at Transport layer is still remain unexplored in the literature. However, thses recent studies [46, 15] focus on analyzing communication between only a pair of nano-devices. Such studies helps in deciding efficient transmission from the perspective of point-to-point communication. However, network-level communication remains beyond the scope of these studies, which is utmost important for investigating the behavior of WNSN.

Communication among nano devices is emerging to the direction of ad-hoc networks due to having special characteristics. Many ad-hoc routing protocols such as AODV, DSR, DSDV, TORA, and OLSR have been proposed for wireless sensor networks (WSNs) and their performances have been investigated in [48], [49], [50] considering the fact of having of low power, limited resource, and small communication range of sensor nodes. In [48], [51], and [52], the superiority of AODV has been explored over other routing protocols for WSNs. However, owing to some unique characteristics of nano devices such as antenna behavior, very small communication range (i.e., few nanometers), limited operating capabilities, and radiation over terahertz bands (i.e., 0.1-10 THz), it cannot be concluded that WNSNs can directly adopt the protocols. Besides, it cannot be guaranteed that WNSNs would also perform better adopting these protocols without conducting any experiments. Therefore, there is a need to analyze the diverse behavioral impacts of these routing protocols in WNSNs and to determine whether any modification in the Network and Transport layers would improve the performance of WNSNs.

Chapter 3

System Model of Wireless Nanosensor Networks

In our study, we consider a wireless nanosensor network (WNSN) operating over a target area to collect information. We present network architecture and operational physical interface of our considered WNSN in this section.

3.1 Network Architecture

WNSNs support communication among nano devices, as well as their interaction with the external world such as Internet. Such networks consist of three different types of nano devices [1] namely nanonode, nanorouter, and nanogateway. Fig. 3.1 presents a network architecture consisting all the three types of devices.

- Nanonodes: Nanonodes are small and simple devices having limited energy and small transmission range. They can be deployed into a target area for collecting certain information. The devices can act as nanosensors. They have limited memory, and can only transmit over very short distances, mainly because of their reduced energy and limited communication capabilities. Such nanonodes with communication capabilities can be integrated in all types of things such as books, keys, or paper folders.

- Nanorouters: Nanorouters are nano devices having sizes and resources larger than the previous ones. They act as connector between nanonodes and nanogateway. They are in

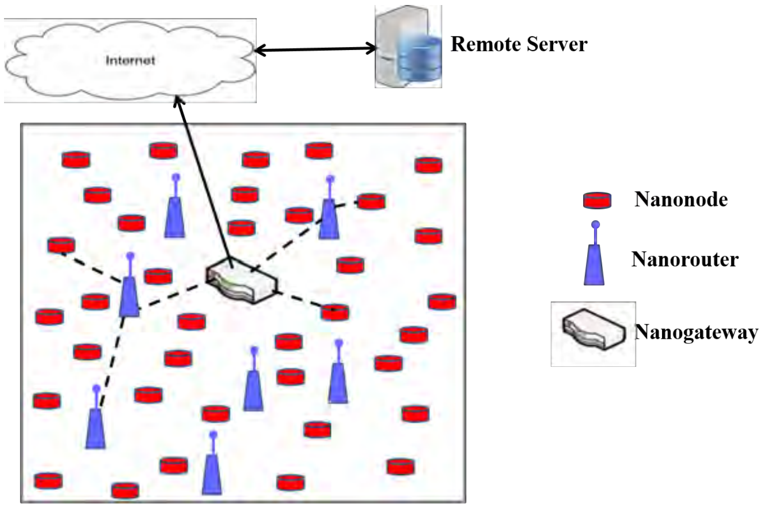


Figure 3.1: Network architecture of a WNSN

charge for processing information forwarded from nanonodes as well as from a nanogateway. They are suitable for aggregating information coming from limited nanonodes. In addition, nanorouters can also control the behavior of nanonodes by exchanging very simple control commands (on/off, sleep, read value, etc.).

- Nanogateway: Finally, nanogateways are complex high-end nodes able to act as gateways between the nanonetwork and the external world. They should be able to convert WNSNs messages to that of a conventional network such as WiFi, cellular networks, etc., and vice versa. Nanogateway can receive information from nanorouter or nanonodes and can process this information. It can also send this information to any device such as computer, mobile etc.

In general, in a WNSN, one nanogateway is placed near the center of the coverage area. All the other nanodevices, i.e., nanorouters and nanonodes, are deployed around the nanogateway over the area. The nanogateway communicates with a nanonode either directly or through nanorouters. All the nano devices including nanorouter and nanonode are placed randomly or in a grid around the nanogateway. This types of scenario can be utilized in a large number of WNSNs applications in real life.

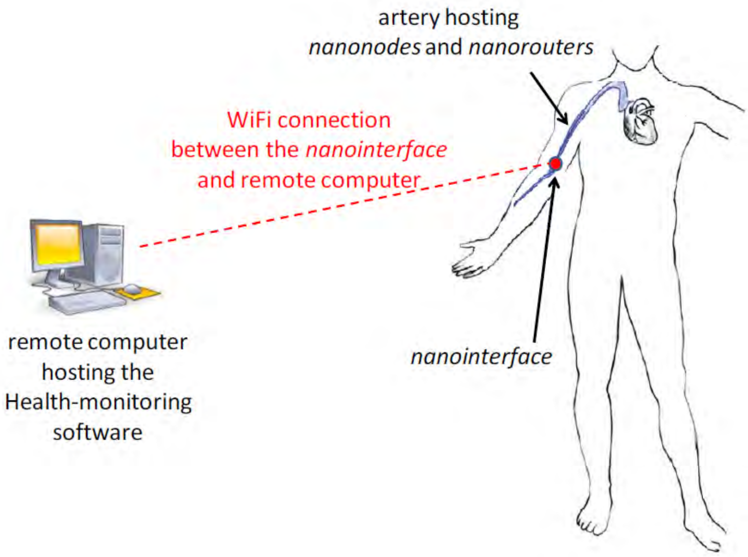


Figure 3.2: Network architecture of a health-monitoring system [1]

3.2 Applications of Adopted Architecture

Most of the existing studies [1] consider the nano devices deployed in a human body or artery. The nanogateway or nanointerface placed inside or outside the human body in a fixed place which communicates with outside computer through electromagnetic communication. This types of scenario is illustrated in Fig. 3.2. Here, all the nanonodes and nanorouters are deployed in the artery and nanointerface is placed in a fixed location. We are considering WNSNs which operate in smart office, smart cloth store, book store, file store, or monitor room, locating office belongings, etc. All the nanonodes are considered to be integrated with books, files, clothes, etc. Therefore, the nanonodes are deployed randomly. The nanorouters are also deployed randomly over the coverage area. Finally, we assume the nanogateway placed in the center of the coverage area to receive information from all directions of the whole area.

Our considered network architecture is demonstrated in Fig. 3.3 where the nanonodes are assumed to be integrated with files. Besides, the nanorouters are placed randomly in the coverage area to enable routing as nanorouters have longer transmission range than nanonodes. Further, the nanogaetway is placed in the center of the coverage area. We assume this network architecture to be adopted for other real life future application scenario such as cloth store, smart office, etc.

- Smart office: In an interconnected office, a nanonode can be embedded in every sin-

Figure 3.3: Network architecture of a file store

gle object. These nanonodes can communicate with nanogateway directly or through nanorouters. Nanaogateway can connect to the Internet by connecting to a device such as a mobile or computer. As a result, a user can keep track of all its professional and personal item in an effortless fashion.

- Smart cloth store: In a cloth store, all the cloths can be equipped with nanonodes. These nanonodes can connect to nanogateway. Nanogateway can allow the whole system to be connected to the external world. Nanogateway can connect to Internet or Wifi. Therefore, user can keep track of all the cloths. The location of a specific cloth can be determined very easily.

- Smart file store: Like cloth store, in a file store all the files can be integrated with nanonodes (Fig. 3.3). The nanorouters can be deployed among the files to keep the whole system connected. Nanogateway connects to the Internet. As a result, all files can be located efficiently.

3.3 Physical Interface and Radio Propagation

In a WNSN, all the nano devices communicate with each other using electromagnetic wave based wireless communication. To enable electromagnetic (EM) communications in very short distances, terahertz band communication [53] is anticipated as a key solution in wireless communication. THz communication can enable a plethora of diversified and many envisioned applications in many fields in real life. The THz Band is the spectral band that spans the frequencies between 0.1 THz and 10 THz. The frequencies below and above this band have been widely studied, however this band is still very little explored in the literature. The possibility and potential applications of THz use in the range of 0.1 - 10 THz to enable communication in very short transmission ranges has been discussed [53, 54, 55, 56, 57, 58, 59]. The IEEE recently established a working group to study the potential applications of the THz band. The IEEE 802.15 Wireless Personal Area Networks (WPAN) Study Group 100 Gbit/s (SG100G) [60] Wireless is studying towards THz Band communication to enable multi-Gbps and Tbps links. The THz band is not suitable to be used for far field communication as it demands high power for transmission [61]. Nonetheless, it can be easily utilized for low distance communication.

THz Band offers a larger bandwidth, which ranges from tens of GHz up to several THz depending on the transmission distance. This band can support very large bit-rates for distances below one meter and also enables simple communication mechanisms for nano devices. Electromagnetic communication for nanonodes operates in the 0.1-10 THz band, which is different from conventional wireless carrier based communication model. A network of resource-limited THz operating nanonodes demands specialized propagation model and nano-antenna design. Physical interface and propagation model of THz communication is very different from the Gigahertz (GHz) channel due to the unique properties of THz communication such as higher propagation loss and extra molecular absorption loss [40]. Therefore, propagation models pertaining GHz channel cannot be adopted directly for the THz channel. In THz band, the signal strength can be diminished because of the propagation loss and molecular absorption loss. To overcome the problems in THz communication, traditional model of nano-antenna can not be used. As nano-antenna is one of the most crucial components of nano device, emphasis should be given to specialized nano-antenna design which is necessary for THz communication.

Simply reducing the size of classical antenna would result in very high frequencies. Conventional metals might be unable to perform in its traditional way for such high frequencies [62]. For example, a one-micrometer-long dipole antenna would resonate at approximately 150 THz which would impose very high power and path loss. Owing to the property of having very limited power of nano devices, the feasibility of wireless nanosensor networks would be compromised if the classical antennas is used by simply reducing their size. Moreover, it is not clear how a miniature classical antenna could be supervised to operate at these very high frequencies. Further, it remains unknown that how intrinsic material properties of common metals would work at the nanoscale. Hence, the use of supportive nanomaterials to engineer miniature antennas can assist in addressing the above mentioned limitations.

One of the most recent proposed alternatives to support THz Band communication and miniature antenna is based on the utilization of graphene. Graphene was first introduced from High Ordered Pyrolytic Graphite (HOPG) in 2004 [63, 64] and has grasped much interest of researchers owing to its unique properties. Many devices are rebuilt using graphene based on its unique electric properties. For example, for field-effect transistors and interconnects , high speed is achieved due to the special energy band structure and ultrahigh electron mobility in graphene. Another promising research topic is graphene-based nano-antennas [65, 66, 42] .

Graphene is a one-atom-thick nanomaterial which was experimentally procured for the first time in 2004 [63, 64]. Graphene has unique electrical, physical and optical properties. It is often called as “the wonder material” of the 21st century [67]. As a result, graphene-based nano-antennas have been in focus for enabling communication in WNSNs utilizing operating spectrums over terahertz band (0.1-10 THz) [66, 68].

Graphene is a one atom thick planar sheet of bonded carbon atoms in a honeycomb crystal lattice. This honeycombs slow down electrons 300 times. Hence, the wavelengths (lower frequencies) get larger which can be used with small antennas. Graphene-based nano-antennas have a smaller size due to their slow wave property [66, 69], and resonate with a higher radiation efficiency owing to the higher electron mobility in its nano-scale structure [65]. The conductivity of graphene has been investigated for frequencies that range from the Terahertz Band (0.1-10 THz) up to the visible spectrum [70, 71]. Among different types of nano-antennas, plasmonic nano-antennas [2] can be easily built by using graphene material.

Graphene-based plasmonic nano-antenna or graphennas [21], just a few micrometers in size, are envisioned to radiate electromagnetic waves in the terahertz band (0.1-10 THz) [40], [68]. The propagation of graphene-antenna is called Surface Plasmon Polariton (SPP) waves which can produce EM waves coupled to the surface electric charges at the connection between a metal and a dialectric material [2]. In graphene, SPP waves propagates with much lower

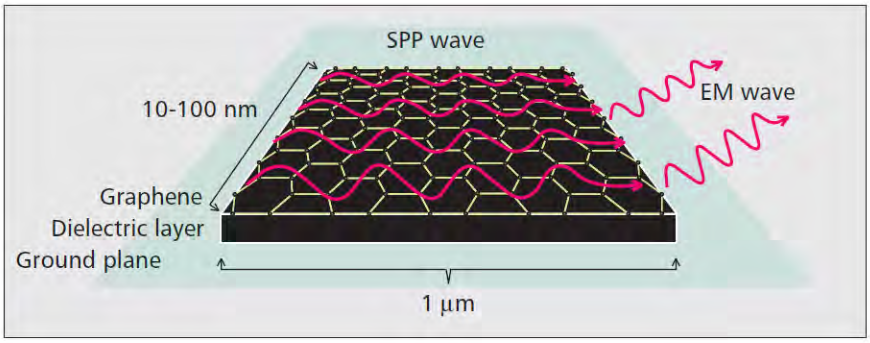


Figure 3.4: A graphene-based plasmonic THz Band antenna [2]

frequency. The propagation wave vector of SPP waves in graphene can be up to two orders of magnitude above the propagation wave vector in vacuum. The equivalent electrical size of a plasmonic patch antenna is much larger than its physical dimensions, owing to the much lower speed of SPP waves in the plasmonic antenna compared to that of free space electromagnetic waves in classical metal antennas. This is the main difference between a metallic antenna and a plasmonic patch antenna. This turns into much more precise antennas which can be integrated into nano devices. The structure of a graphene patch antenn is shown in Fig. 3.4.

For example, a one micrometer long and ten nanometers wide plasmonic nano-antenna is expected to radiate in the terahertz band (0.1-10 THz) [2]. Since graphene-based antennas resonate at much lower frequencies and with a higher radiation efficiency compared to that of metallic antennas [40], [62], graphene antenna can be integrated into nanodevices to radiate over the terahertz band. Therefore, we assume that all the nanodevices in our proposed WNSN are equipped with graphene-enabled antenna. More specifically, we consider all the nano devices will radiate at the frequency of 1 THz and the nano devices are equipped with graphene antennas that are assumed to radiate over that frequency.

Note that the classical propagation model, such as Two Ray propagation model [72] mostly operates based on the height of the antenna. Thus such classical models can not be applied for graphene-based nano antenna. As a result, specialized propagation model considering the path loss is needed to be adapted for graphene-based nano-antennas. Considering the high path loss in free space, we assume that nano devices in a WNSN radiate following the radio propagation model (Eq. 3.1) over the terahertz band using graphene-enabled plasmonic nano patch antenna [73]. The radio propagation model is presented below.

$$G_T = \left(\frac{4 \times \pi \times D}{\lambda}\right)\left(\frac{P_R}{P_T}\right)^{\frac{1}{2}} \tag{3.1}$$

The path loss of a signal is computed by taking the ratio of transmitted power of transmitter and received power of receiver. Therefore the path loss can be calculated as follows:

$$\frac{P_T}{P_R} = \left(\frac{1}{G_T}\right)^2 \times \left(\frac{4 \times \pi \times D}{\lambda}\right)^2 \tag{3.2}$$

where, G_T is the gain of the antenna of transmitter, P_T and P_R are the transmitted and received power respectively, λ is the wave length, and D is the distance between the two nano devices. This propagation model is proposed for patch antenna to support THz communication at nano scale in [73].

The above equation actually implies the Friis Transmission Formula [74]. Free Space model is used to obtain the path loss of wireless communication when line-of-sight path through free space (usually air) exists between transmitter and receiver with no obstacles nearby to cause reflection or diffraction. The free space path loss can be obtained from Friis transmission equation. The Friis transmission equation provides the power received by an antenna from another antenna that is transmitting power at a distance under ideal conditions. The formula was derived by Herald T. Friis at Bell Labs in 1945. We consider each nano device will radiate using the propagation model (Eq. 3.1). We incorporate this propagation model in the network simulator `ns-2` to enable THz communication. We perform necessary customizations in `ns-2` to integrate this model.

Considering the network model, physical interface, and radio propagation model, we evaluate the performance of a WNSN. To do so, we design a WNSN as network architecture mentioned above and integrate propagation model at the physical interface in `ns-2`. We focus on two different layers of operation in the network, the Network layer and the Transport layer. We elaborate our performance evaluation and proposed methodology of performance enhancement in the next chapter.

3.4 Difference from Classical Interface and Radio Propagation

For wireless electromagnetic communication, there exist several radio propagation models. The radio wave propagation pathloss should be predicted accurately, as the path loss represents the difference between the power transmitted and the power received at the destination. The optimization of the system and sufficient radio coverage are performed using the pathloss information. Pass loss model helps to figure out what amount of transmitted power is required to cover the desired area. Many propagation models have been proposed by the researchers for various scenarios. Here, we describe some basic propagation models for wireless communication and also point out the differences between this propagation models and our used one.

3.4.1 Free Space Model

If there exist one ray between the transmitting antenna and the receiving antenna (usually termed as the line-of-sight case), then free space model is used. This model is utilized in scenarios such as satellite/space communications [75]. Here, the received power can be computed using the widely known Friis transmission formula, which is as follows [75]:

$$P_r = P_t \left(\frac{\lambda}{4\pi r} \right)^2 G_t G_r \tag{3.3}$$

where P_r is the received power, P_t is the transmitted power, G_t and G_r are the gains of the transmitting and receiving antennas, respectively and r is the distance between the transmitting and receiving antennas. If the antenna is considered as an isotropic antenna, then it can be assumed that $G_t = G_r = 1$. For ideal conditions, using omnidirectional antennas transmitter's gain and receiver's gain will be equal. Therefore, the pathloss L_P can be obtained from the Eq. 3.3 as:

$$L_P = 10log_{10} \left(\frac{P_t}{P_r} \right) = 20log_{10}f + 20log_{10}r - 147.6(dB) \tag{3.4}$$

where f is the frequency. Here, from the above equation, we can see that the pathloss is proportional to the frequency squared and the distance squared. The larger the distance, the larger the pathloss and the higher the frequency, the larger the pathloss. For a fixed distance or frequency, the pathloss is 20 dB/decade [75].

Our used propagation model differ from this free space path loss model. In this model, both G_t and G_r are considered for path loss calculation. However, we have used the path loss model where the only G_t is considered [73]. Here, the G_t and G_r are considered as equal.

3.4.2 Two-ray Propagation Model

It is also termed as Plane Earth Model. In many terrestrial communications scenarios such as radio broadcasting and radio communications in rural environments, the two-ray propagation model can be applied. The transmitted signals reach the destination by the line-of-sight path and the path reflected by the ground [75]. As the signals may be combined constructively or destructively relying on the reflection coefficient of the ground and the phase difference of these two rays, hence the result becomes complicated. The path difference between these two rays is calculated as follows:

$$\Delta r = \sqrt{(h_1 + h_2)^2 + d^2} - \sqrt{(h_1 - h_2)^2 + d^2} \approx \frac{2h_1h_2}{d} \tag{3.5}$$

where h_1 and h_2 are the height of the transmitting and receiving antennas, and d is the distance. When this difference is half of the wavelength, the phase difference is 180 degrees (out of phase), the separation is obtained by the following equation and is called the first Fresnel zone distance.

$$d_f = \frac{4h_1h_2}{\lambda} \tag{3.6}$$

There is some points to be noted out. When the separation of the two antennas is smaller than this distance, $d < d_f$, the pathloss is about 20 dB/decade. On the other hand, when the separation is greater than this distance, $d > d_f$, the pathloss is 40 dB/decade,

$$P_r = P_t \left(\frac{h_1h_2}{d^2} \right)^2 \tag{3.7}$$

It can be observed from the Eq. 3.7, the higher the transmitting and receiving antennas, the smaller the pathloss. It can be seen that the two-ray propagation model depends on the heights of the transmitting and receiving antennas, which is the main difference with our used propagation model. The propagation model which we have used has been considered for nano devices, hence, in this model, the height of the antenna is not applicable.

3.4.3 Multipath Models

The multipath case is considered for more than two rays. However, no analytical equations have been developed to provide an accurate estimation of the radio propagation pathloss for the multipath case. Nonetheless, empirical and statistical Most of the popular outdoor radio pathloss prediction tools are based on Okumura and Hatas formulation. This formulation is based on a huge amount of measured data for frequencies between 100 MHz and 3 GHz [76]. Many researchers have proved that indoor pathloss actually follows the distance power law as the following equation for indoor scenarios.

$$L_P(d) = L_P(d_0) + 10nlog\frac{d}{d_0} + X, dB \tag{3.8}$$

where d_0 is the reference distance (normally it is 1 m), the power index n depends on the frequency, surroundings and building type and X represents a normal random variable in dB having a standard deviation of σ dB. It is apparent that the value n is normally (but not always) larger than 2, which is the free space case. It also shows that the higher the frequency, the larger n for the same scenario.

In this model, the power index depends on the frequency along with surroundings and building type. However, in our used propagation model, we have considered a small coverage area for nano devices. Hence, power index and other similar characteristics are not suitable for predicting the propagation of nano-antennas.

Chapter 4

Proposed Methodology for Performance Enhancement in WNSNs

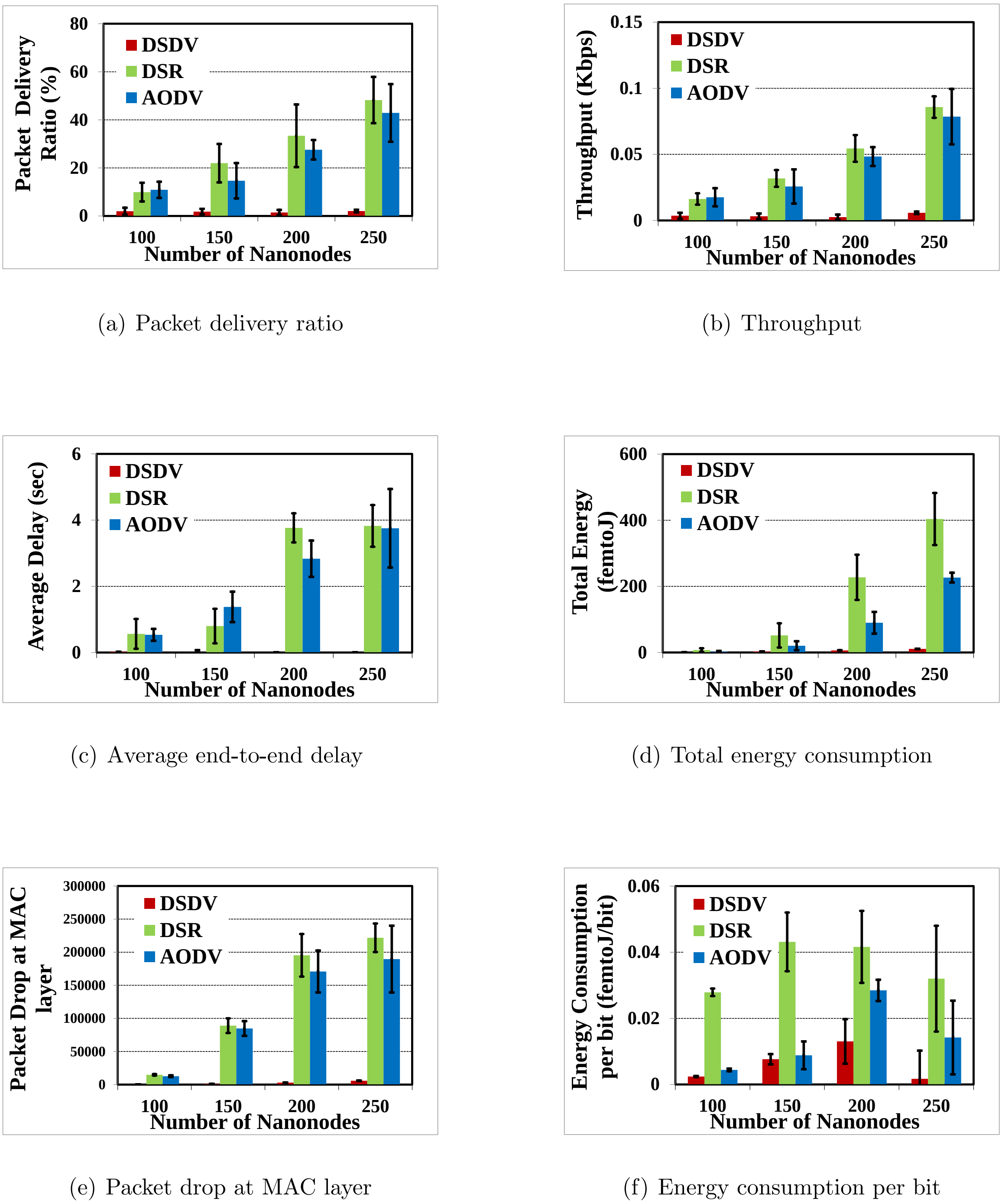
To enhance the performance of WNSNs, we mainly focus on improving operational protocols. Here, our goal is to make the packet forwarding and end-to-end data delivery process efficient. Therefore, we narrow down our focus on the Network layer and the Transport layer.

4.1 Performance of Classical Network Layer Protocol

First, we analyze performance of classical routing protocols over WNSNs. Here, we adopt AODV, DSDV, and DSR as the classical routing protocols as they are well known for having the capability of packet forwarding with minimum number of hops. In our analysis, only nanogateway generate packets. Here, all the nanonodes and nanorouters are placed randomly. Besides, we consider UDP at the Transport layer and MAC 802.11 at the MAC layer.

In such a setting, we analyze performance of the classical routing protocols. To perform the analysis, we conduct event-based simulation. We adopt `ns-2` as the simulation platform. In our simulation, we adopt detail settings similar to that presented later in the chapter.

We perform our simulation with varying number of nanonodes and nanorouters. We present our simulation results with nanonodes and nanorouters having combinations of numbers [100,30], [150,45], [200, 60], and [250, 75] in Fig. 4.1. Here, the transmission ranges of nanonodes, nanorouters and nanogateway are 0.1m, 0.2m, and 0.5m respectively. In Fig. 4.1,



(a) Packet delivery ratio

(b) Throughput

(c) Average end-to-end delay

(d) Total energy consumption

(e) Packet drop at MAC layer

(f) Energy consumption per bit

Figure 4.1: Comparison of performance with different classical routing protocols

we present simulation results from the perspective of diversified network parameters such as packet delivery ratio, throughput, end-to-end delay, total energy consumption, packet dropped at MAC layer and energy consumption per bit to study the overall and specific impacts of different classical routing protocols.

The simulation results exhibit a mix of performance outcomes through using the classical routing protocols. Here, as per Fig. 4.1(a) and 4.1(b), AODV performs better for lower number of nodes and DSR performs better for higher number of nodes in terms of delivery ratio and throughput. DSDV, the worst choice for these, on the other hand, exhibits the smallest delay as per Fig. 4.1(c). Also, DSDV incurs the lower number of dropped packets at the MAC layer. However, these benefits are not enough as the throughput obtained by DSDV is very low compared to other two alternatives (Fig. 4.1(b)). Now between the other two protocols, DSR consumes significantly high energy as per Fig. 4.1(d). Thus, considering the necessity of having very limited energy for nano devices, DSR should be taken out of the race for nanonetworks. Fig. 4.1(e) presents packet drop for all the routing protocols. Here, though packet drop is lowest with DSDV, DSDV is not well suited, as it does not perform well for other network metrics such as packet delivery ratio, and throughput. AODV shows lower packet drop compared to DSR. Energy consumption per bit is demonstrated in Fig. 4.1(f) where AODV exhibits lower energy per bit than DSR. Thus, the analysis reveals that, considering all the trade offs, AODV should be considered as the best possible solution among the considered classical routing protocols for nanonetworks. Therefore, we adopt AODV as the basis of our performance enhancement at the Network layer.

4.2 Modification in the Network Layer

We exploit the specific architectural design of WNSNs to propose a new routing protocol. Our proposal is based on AODV, which is found to be best one in our earlier study. Now, to limit the complexity of routing operations and to improve the overall performance, we propose a hierarchical AODV for WNSNs. According to the conventional AODV (Ad hoc On-Demand Distance Vector) routing protocol, nanogateway forwards RREQ (Route Request) packet to find out a path to the destination nanonode. The RREQ packets get forwarded by the intermediate nanorouters and nanonodes to find out the optimal path having the minimum

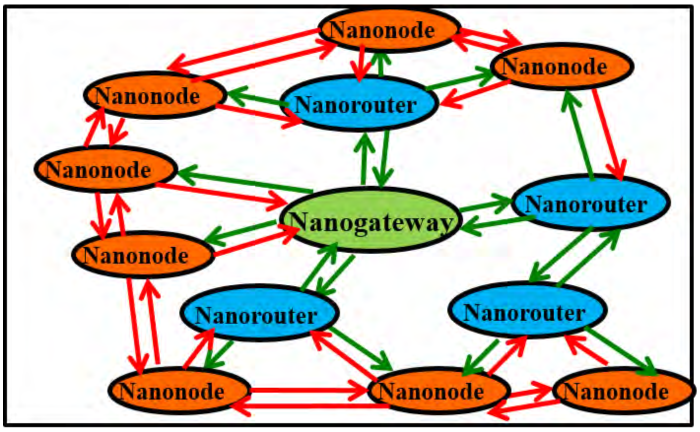


Figure 4.2: Conventional AODV

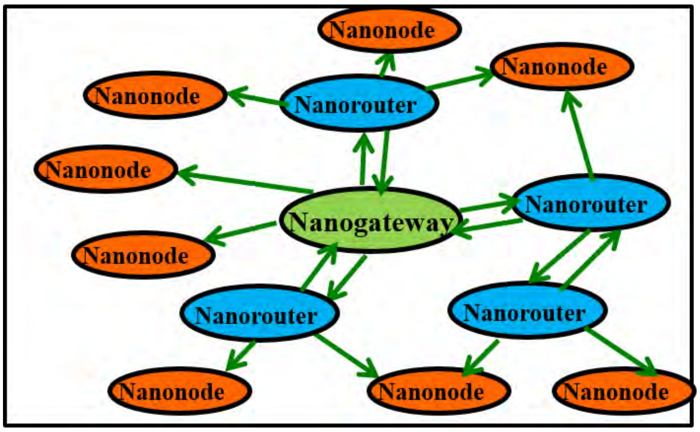


Figure 4.3: Hierarchical AODV

number of hops.

In our proposal, we consider a hierarchy in RREQ packet forwarding. Here, nanogateway will forward RREQ packets to all the devices within its transmission range, however, RREQ packets will be forwarded only by the intermediate nanorouters, not by the intermediate nanonodes. Therefore, only the nanorouters will take part in packet forwarding to establish multi-hop paths. We enforce participations only by the nanorouters in intermediate packet forwarding as nanorouters have higher energy and capabilities than that of nanonodes. In this way, each message generated by the nanogateway will be propagated only by the nanorouters within the WNSN. Therefore, path from nanogateway to nanonodes might not be the path with minimum number of hops, however the intermediate nanorouters will eventually establish the path. Fig. 4.3 presents the architecture of proposed hierarchical AODV. When the destination nanonode is found, RREP (route reply) packet is forwarded back to the path generated

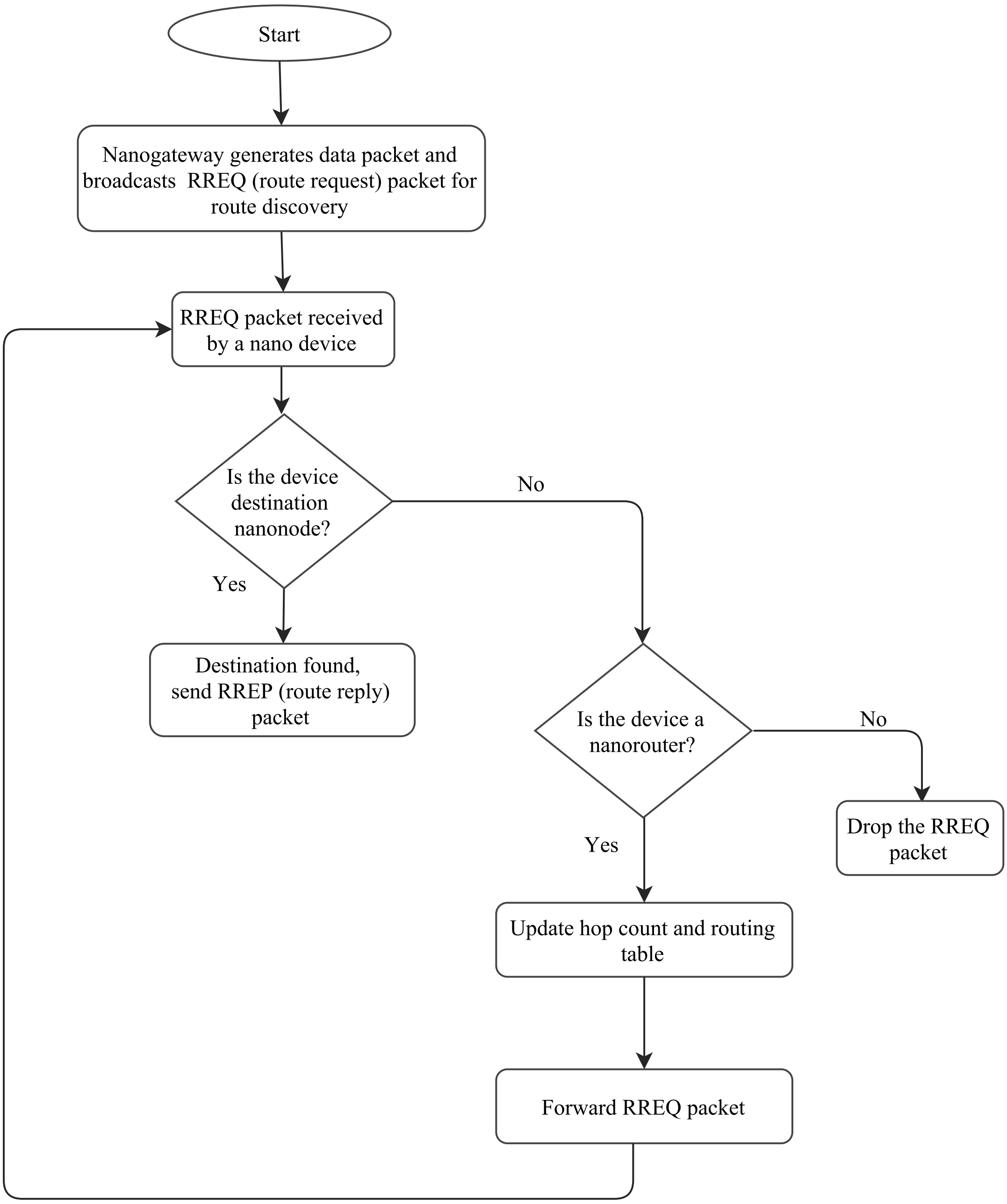


Figure 4.4: Flow of hierarchical AODV

by intermediate nanorouters. Upon receiving the RREP packet, each nanorouter updates its routing table as it has a path to destination and forward RREP packet to the intermediate nanorouters forming path with minimum number of hop count. The flow of this hierarchy in RREQ packet forwarding is demonstrated by the Fig. 4.4. The hierarchical AODV is also illustrated by the algorithm presented in Algorithm 1

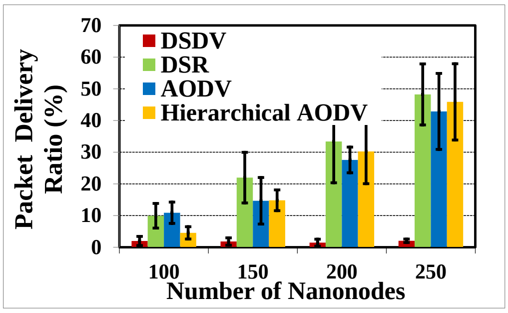
Algorithm 1 Hierarchical AODV

```
Step1: nanogateway creates data packet
Step2: nanogateway create RREQ packet
Step3: nanogateway broadcast RREQ packet
Step4: nano devices receive RREQ packet
for each nano device within transmission range do
    if the device is destination then
        destination found
        send RREP packet
    else
        if the device is nanorouter then
            update hop count
            update routing table
            forward RREQ packet
            go to Step4
        else
            drop the RREQ packet
```

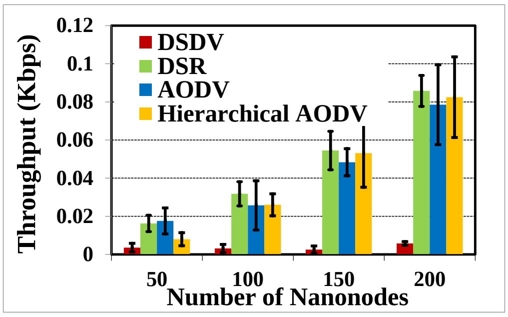
It is worth mentioning that there exists a few research studies [16], [17] in the literature pertaining hierarchical AODV. However, most of the existing studies are mainly focus on dynamic cluster based hierarchical architectures for mobile ad-hoc networks. To the best of our knowledge, a static hierarchical AODV for wireless nano sensor devices is yet to be explored in the literature. Therefore, in this work, we device a static hierarchical AODV by allowing forwarding of RREQ packets only by the nanorouters.

We perform simulation with our proposed hierarchical AODV and compare the results with other routing protocols in Fig. 4.5. Fig. 4.5 reveals that our proposed modification achieves second best outcomes compared to all performance metrics. More importantly, performance of our proposed modification is very close to that of the best options among the classical alternatives.

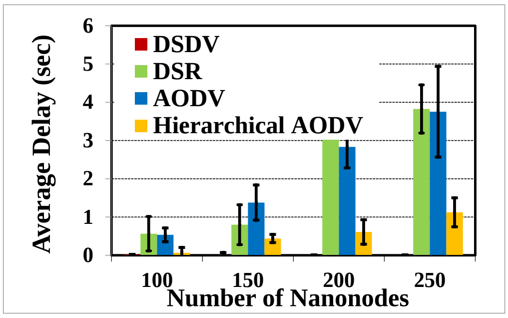
Note that we perform simulation so far using the MAC layer protocol 802.11. MAC 802.11 is suitable for long-range data transmission and high bandwidth. Reason behind the suitabil-



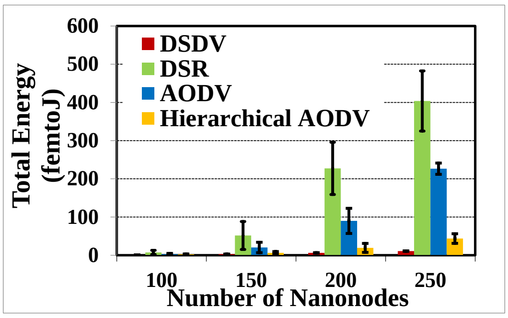
(a) Packet delivery ratio



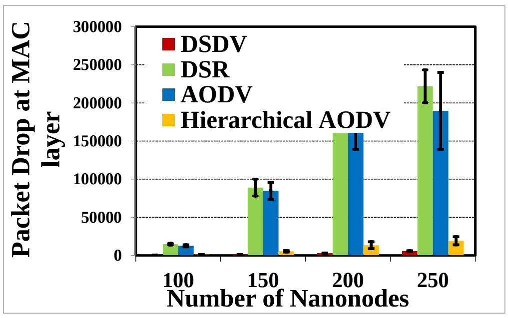
(b) Throughput



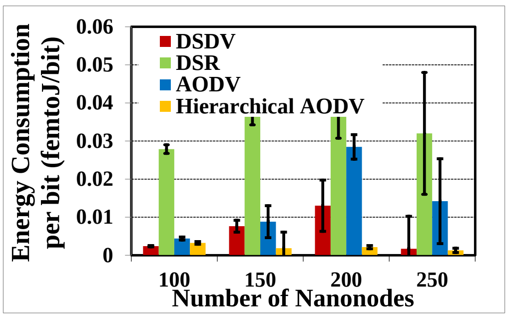
(c) Average end-to-end delay



(d) Total energy consumption

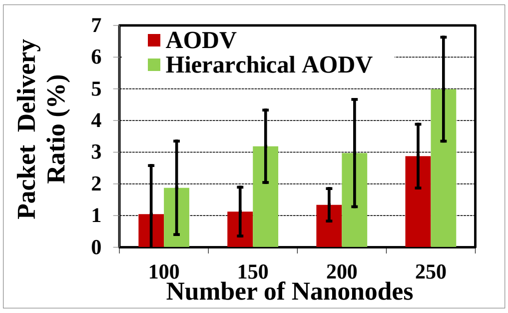


(e) Packet drop at MAC layer

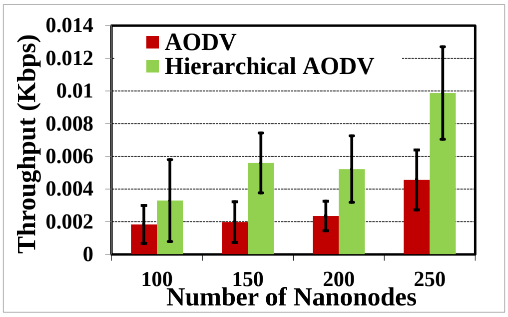


(f) Energy consumption per bit

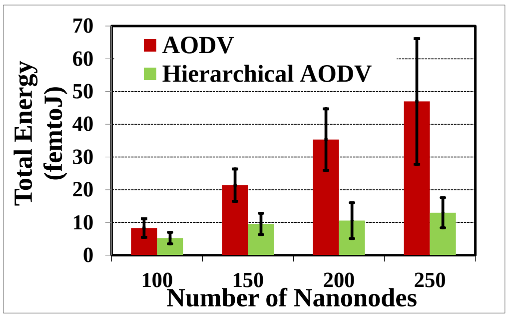
Figure 4.5: Comparison of performance of different routing protocols including the proposed hierarchical AODV



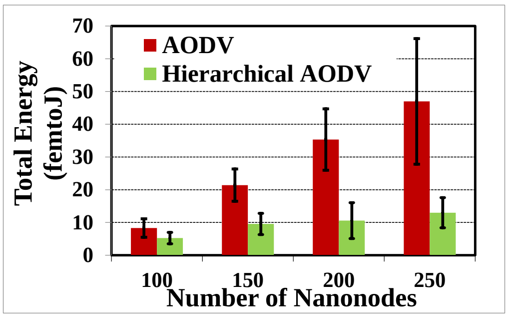
(a) Packet delivery ratio



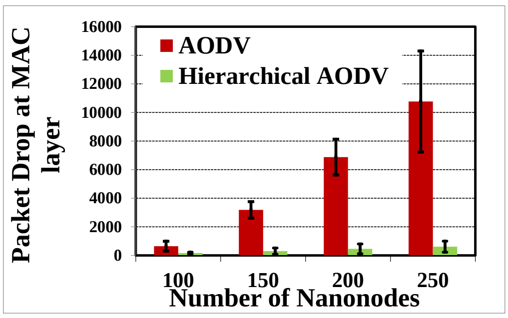
(b) Throughput



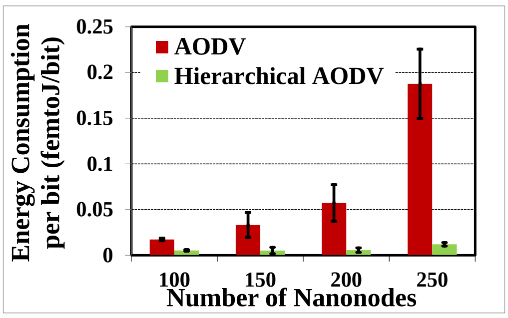
(c) Average end-to-end delay



(d) Total energy consumption



(e) Packet drop at MAC layer



(f) Energy consumption per bit

Figure 4.6: Comparison of performance of different routing protocols while using 802.15.4 in the MAC layer

ity is exploiting the notion of RTS and CTS enabling CSMA/CA to avoid collision. Since 802.11 utilizes RTS and CTS, it performs better with high power and high data rates. On the other hand, the MAC layer protocol 802.15.4 is an energy-efficient MAC protocol that demands limited capacity, and therefore, is suitable for low data rates, short range and low-power communication. Since energy is also one of the most fundamental concerns for nano devices, we explore MAC 802.15.4 for our case.

Considering the variation in MAC layer, we perform our simulation over the WNSNs using MAC 802.15.4. Here, as we have already found the best in WNSNs, we simulate only AODV with MAC 802.15.4 as the benchmark along with our proposed hierarchical AODV to evaluate its performance. Fig. 4.6 shows the impact of using MAC 802.15.4 in AODV and hierarchical AODV. The figure confirms that our proposed hierarchical AODV significantly performs better than the classical AODV even while using 802.15.4 as the MAC layer protocol. Next, to further boost up the performance enhancement, we propose a modification in the Transport layer.

4.3 Modification in the Transport Layer

From Fig. 4.5(a) and Fig. 4.6(a), we find that packet delivery ratio while using 802.15.4 drastically falls since there is no mechanism to avoid collision. On the other hand, 802.11 utilizes RTS and CTS control to avoid such collisions, however, for nanodevices RTS and CTS consume significant amount of energy. Now, to improve the packet delivery ratio while using 802.15.4, we propose an acknowledgement-based UDP protocol in the Transport layer. In conventional UDP, messages are delivered to destination without establishing any connection. There is no mechanism in UDP to verify whether the message has been received by the destination or not. On the contrary, TCP maintains acknowledgement and a congestion window to control traffic over the network and to limit flow of packets. We introduce the notion of acknowledgement and a timeout timer in UDP to double check whether the packet gets delivered to destination.

In our WNSN, we consider that nanogateway will generate messages (data packets) and send to nano devices. After sending a data packet, nanogateway (the sender) will start a timer for this packet to wait for the acknowledgement of the sent packet. After receiving a data packet, nanonodes (the receiver) will send an acknowledgement packet (ACK packet) to acknowledge that it has received the sent packet. Nanogetway will send the next data packet upon receiving

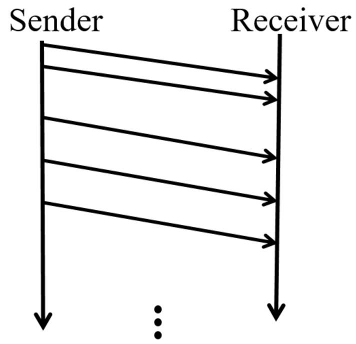


Figure 4.7: Classical UDP

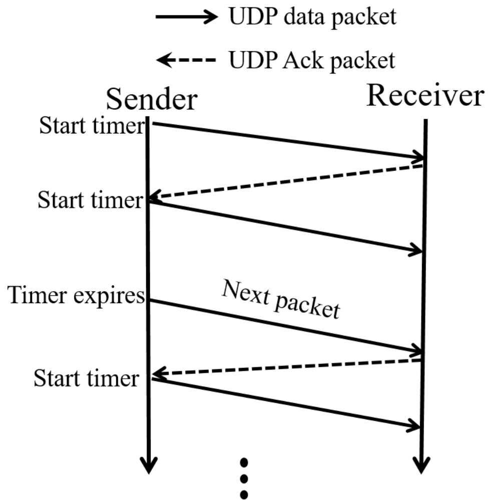


Figure 4.8: UDP with ACK packet and timer

the ACK. If it does not receive the ACK packet within the timer, then it will send the next data packet and start the timer again. Fig. 4.8 depicts the flow of this proposed UDP which regulates its traffic flow. The step by step action of acknowledgement-based UDP is illustrated by the flowchart presented in Fig. 4.9. Algorithm 2 also demonstrates the operations in our proposed ACK-based UDP.

Existing ACK-based schemes [18] utilize finite state machine concept to send or receive ACK packet. In our approach, transmission of data packet from nanogateway depends on ACK packet received from nanonode to control the traffic and to reduce the collisions. Therefore, our proposed ACK-based UDP is an inimitable approach at Transport layer for WNSN.

We perform our simulation with the same network topology using acknowledgement-based UDP and MAC 802.15.4. Fig. 4.10 presents our simulation results. Here, we find better delivery ratio while using modified UDP. However, in the modified UDP, intermittent delay

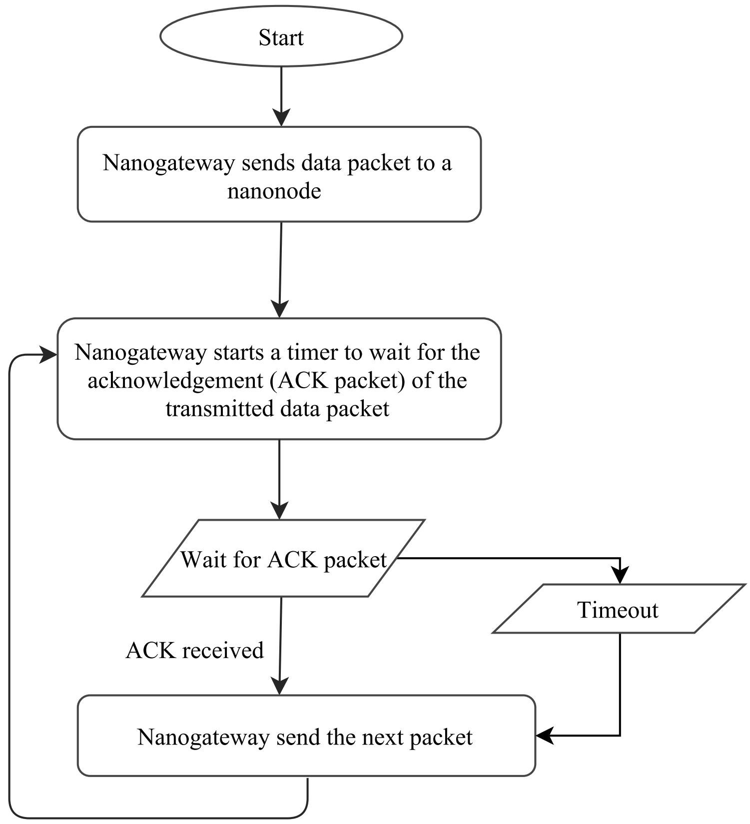
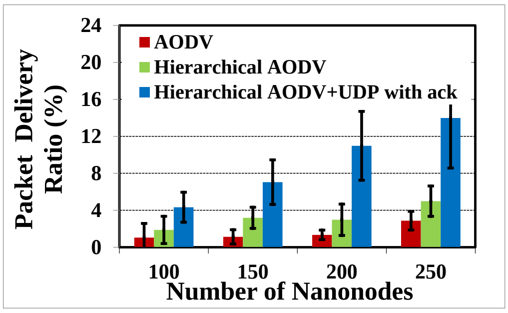


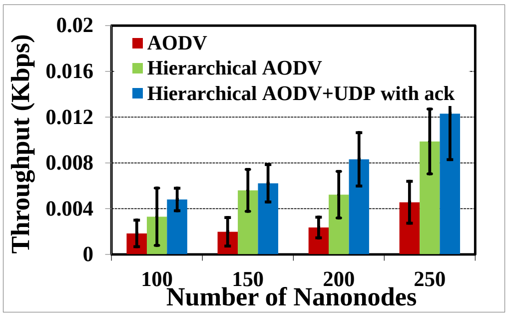
Figure 4.9: Proposed acknowledgement-based UDP

Algorithm 2 UDP with ACK packet and timer

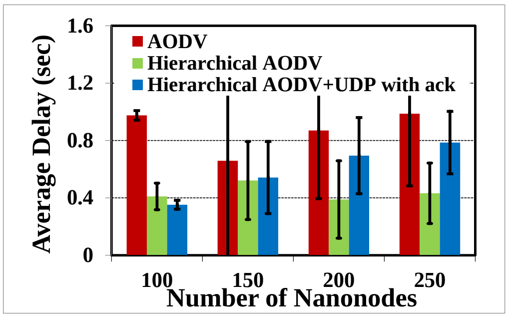
Step1: nanogateway creates data packet
Step2: nanogateway sends data packet
Step3: nanogateway starts a timer
while timer expires **do**
    wait for ACK packet
    if ACK received **then**
        nanogateway sends data packet
        go to Step3
nanogateway sends data packet
go to Step3



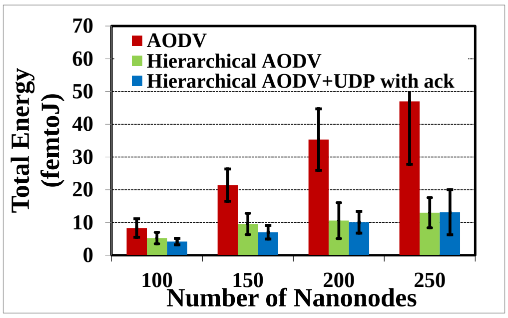
(a) Packet delivery ratio



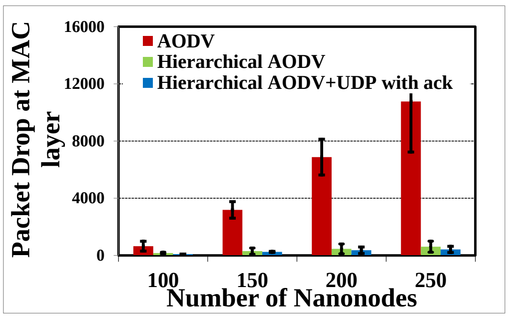
(b) Throughput



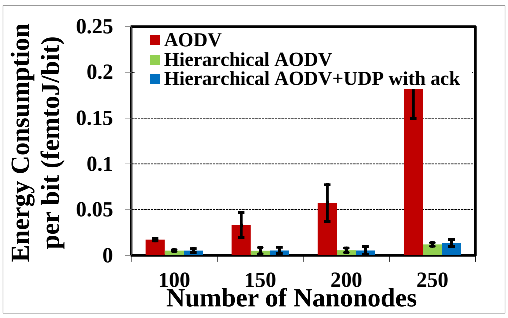
(c) Average end-to-end delay



(d) Total energy consumption



(e) Packet drop at MAC layer



(f) Energy consumption per bit

Figure 4.10: Comparison of performance of different routing protocols along with impact of our modified UDP

gets increased. Apart from this, using the modified UDP exhibits better performances in terms of all other metrics.

Chapter 5

Performance Evaluation

In this chapter, we perform experimental evaluation of our proposed mechanisms through varying different operational parameters. Here, we assume WNSNs is a two dimensional area of 2m×2m. The nanogetway is placed at the center of the area. All the other nodes are deployed randomly over the whole coverage area. Our considered node deployment is illustrated in Fig. 5.1. We elaborate other simulation setting next.

5.1 Simulation Settings

We consider two types of topology-random topology and grid topology. In the grid topology, nanorouters are placed in grid. We perform our simulation using both 802.11 and 802.15.4 MAC layer protocol. We vary the transmission range of nanonodes, and for each variation, we separately vary the number of nanonodes and nanorouters adopting different routing protocols. We consider each sent packet of 16 bytes generated periodically having a 0.2 second interval.

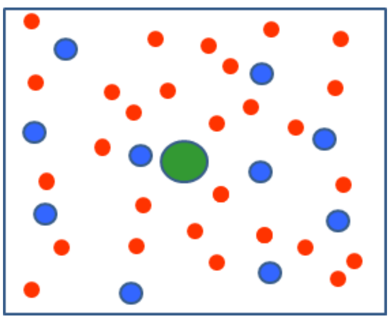


Figure 5.1: Deployment of nanogateway, nanorouters and nanonodes

Table 5.1: Simulation Parameters

Parameter	Value(s)
Number of nanonodes	100, 150, 200, 250
Number of nanorouter	30, 45, 60, 75
Number of nanogateway	1
Area (m^2)	2×2
TX range of nanonodes (m)	[.05, 0.1, 0.2]
TX range of nanorouters (m)	0.2
TX range of nanogateway (m)	0.5
Frequency (THz)	1
Packet size (bytes)	16
Message generation time interval (s)	0.2
Simulation Time (s)	50
Bandwidth (GBps)	1
Transmission energy (femtoJ/sec)	1
Reception Energy (femtoJ/sec)	0.1
Sleep Energy (femtoJ/sec)	0.0005

We consider such a small size of packet as nanonodes are generally expected to possess limited resource, and thus, limited computational capability. Finally, we use UDP and our proposed UDP with acknowledgement at the Transport layer. The values of different parameters of energy are based on [77]. The simulation setting is shown in Table 5.1. With these settings of parameters, we compute the average of 50 simulation runs, each having a duration of 50 seconds.

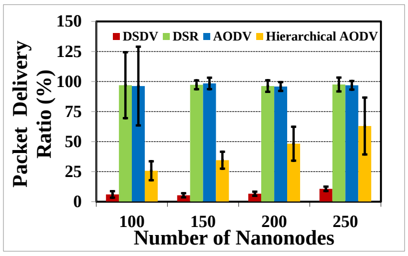
5.2 Simulation Results

We perform simulation of WNSN using two different topology - random topology and grid topology. In random topology, all the nano devices are deployed randomly over the target area. In grid topology, nano devices are placed in fixed grid. The analysis of simulation results for these topologies are presented next.

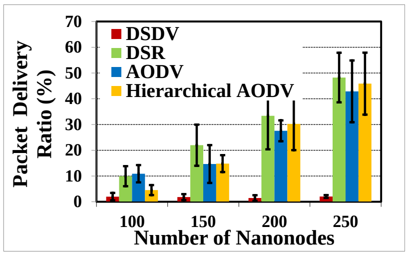
5.2.1 Analysis in Random Topology

We perform simulation of WNSNs in response to varying the transmission range and the number of nanonodes. Fig. 5.2, Fig. 5.3, Fig. 5.4, Fig. 5.5, Fig. 5.6, and Fig. 5.7 illustrate the impact of variation in transmission range of nanonodes on different performance metrics for different routing protocols using the MAC layer protocol 802.11. Fig. 5.2(a), Fig. 5.2(b), and Fig. 5.2(c) demonstrate packet delivery ratio for AODV, DSDV, DSR, and our proposed hierarchical AODV. Delivery ratio increases with an increase in transmission range and number of nanodevices, i.e., nanonodes and nanorouters. AODV and DSR exhibit remarkably better performance for transmission range 0.2m. The packet delivery ratio is almost 100% for AODV and DSR which is depicted in Fig. 5.2(a). However, AODV, DSR, and hierarchical AODV show similar pattern for transmission ranges 0.1m and 0.05m. Average throughput for transmission ranges 0.2m, 0.1m, and 0.05m are presented in Fig. 5.3(a), Fig. 5.3(b), and Fig. 5.3(c). These figures depict that throughput also increases with increase in transmission range and number of nanonodes. The increase in throughput results from increase in packet delivery ratio. Here, AODV, DSR, and hierarchical AODV exhibit similar outcomes for 0.1m and 0.05m transmission ranges. Fig. 5.4(a), Fig. 5.4(b), and Fig. 5.4(b) show the average end-to-end delay for different routing protocols. End-to-end delay increases for higher number of nanonodes. Here, our proposed AODV exhibits smaller end-to-end delay and significantly less fluctuation due to the decrease of forwards of RREQ packets. DSR performs better only for higher value of transmission range.

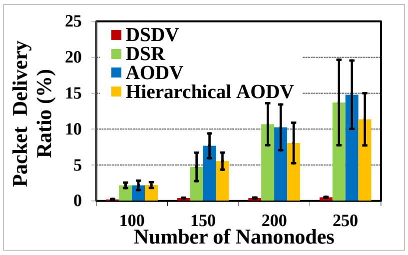
Energy consumption for different transmission range is shown in Fig. 5.5(a), Fig. 5.5(b), and Fig. 5.5(c). The energy consumption of hierarchical AODV is notably smaller than the other routing protocols for all transmission ranges due to the limited forwards of RREQ packet. Since packet forwarding is decreased, therefore less energy is consumed in hierarchical AODV compared to other routing protocols. Fig. 5.6(a), Fig. 5.6(b), and Fig. 5.6(c) present the packet drop at MAC layer. The number of dropped packet increases with an increase in transmission range and number of nanonodes. Once again, the number of packet dropped is significantly smaller in hierarchical AODV. Energy consumption per bit is presented in Fig. 5.7(a), Fig. 5.7(b), and Fig. 5.7(c) for different transmission range. Our proposed AODV consumes less average energy per bit. This occurs due to the decrease in total energy consumption for less number of for-



(a) Tx range of nanonodes is 0.2m

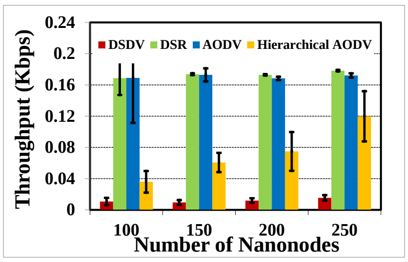


(b) Tx range of nanonodes is 0.1m

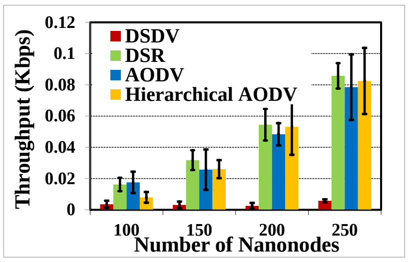


(c) Tx range of nanonodes is 0.05m

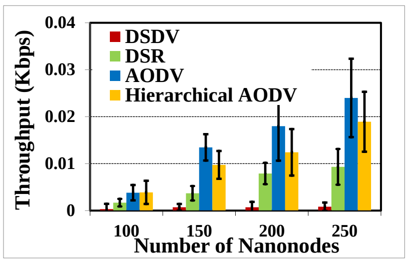
Figure 5.2: Comparison of packet delivery ratio while using 802.11 in the MAC layer



(a) Tx range of nanonodes is 0.2m

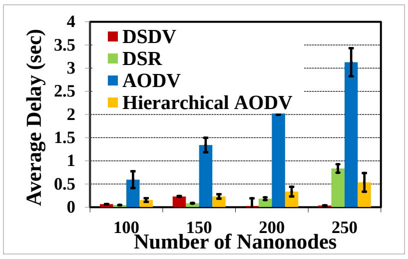


(b) Tx range of nanonodes is 0.1m

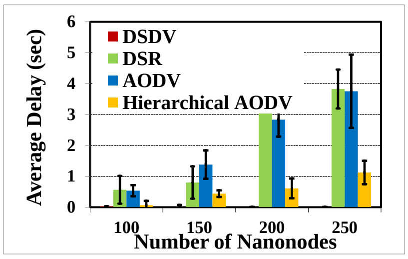


(c) Tx range of nanonodes is 0.05m

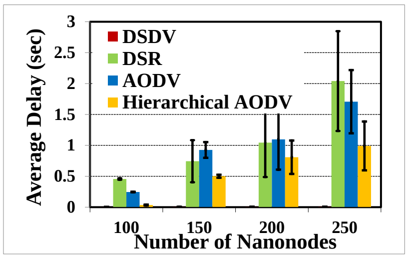
Figure 5.3: Comparison of throughput while using 802.11 in the MAC layer



(a) Tx range of nanonodes is 0.2m

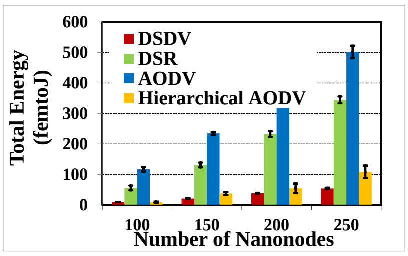


(b) Tx range of nanonodes is 0.1m

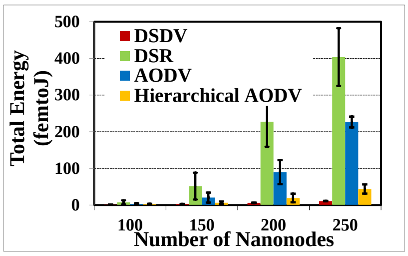


(c) Tx range of nanonodes is 0.05m

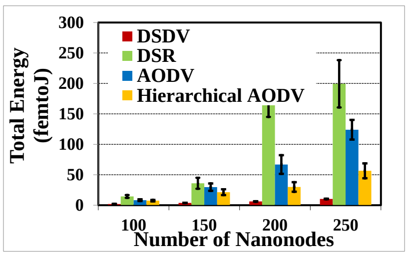
Figure 5.4: Comparison of end-to-end delay while using 802.11 in the MAC layer



(a) Tx range of nanonodes is 0.2m

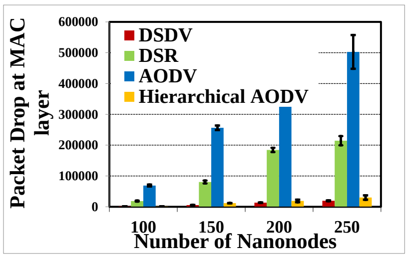


(b) Tx range of nanonodes is 0.1m

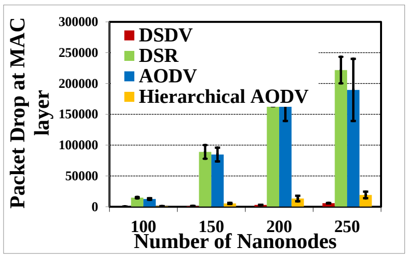


(c) Tx range of nanonodes is 0.05m

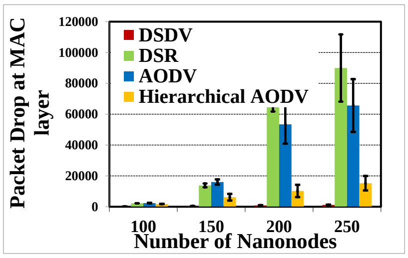
Figure 5.5: Comparison of energy consumption while using 802.11 in the MAC layer



(a) Tx range of nanonodes is 0.2m

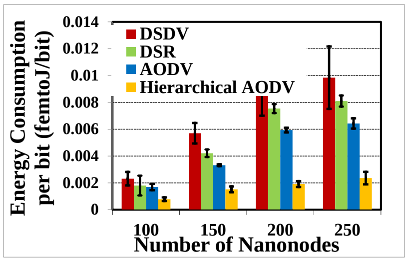


(b) Tx range of nanonodes is 0.1m

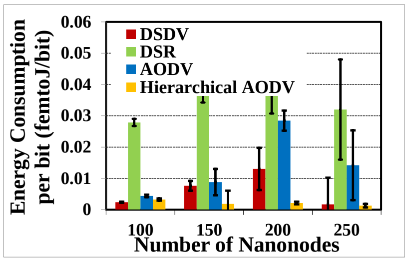


(c) Tx range of nanonodes is 0.05m

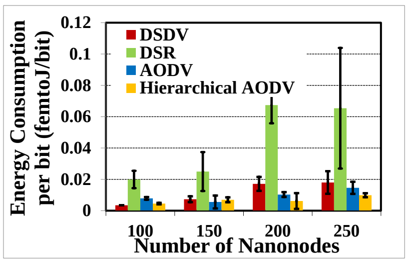
Figure 5.6: Comparison of packet drop while using 802.11 in the MAC layer



(a) Tx range of nanonodes is 0.2m



(b) Tx range of nanonodes is 0.1m



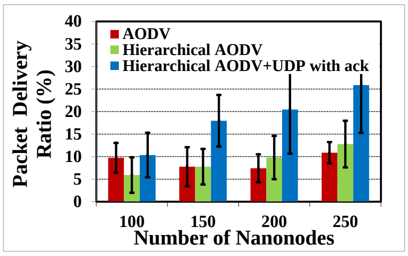
(c) Tx range of nanonodes is 0.05m

Figure 5.7: Comparison of energy per bit while using 802.11 in the MAC layer

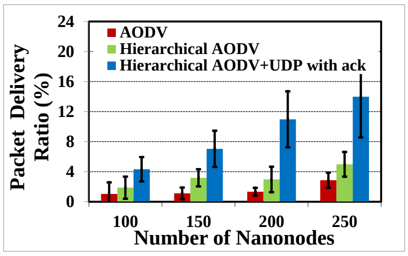
wards. Finally, our simulation results confirm that our proposed modification in the Network layer outperforms other classical routing protocols in terms of average end-to-end delay, energy consumption, energy consumption per bit and packer drop.

To gain insight into the impact of different MAC layer protocol, we further run our simulation with the MAC layer protocol 802.15.4. Fig. 5.8, Fig. 5.9, Fig. 5.10, Fig. 5.11, Fig. 5.12 and Fig. 5.13 demonstrate the impact of variation in transmission range of nanonodes on different performance metrics for AODV, hierarchical AODV and hierarchical AODV with ACK packet. We conduct all our simulation considering the timer value for our modified UDP is 0.8 second. Fig. 5.8(a), Fig. 5.8(b), and Fig. 5.8(c) depict packet delivery ratio for AODV, hierarchical AODV and hierarchical AODV with ACK packet. Delivery ratio increases in response to the increase in transmission range. Hierarchical AODV with ACK packet performs significantly better in delivery ratio. Since data packet is forwarded after receiving ACK packet of the previous sent packet and the flow of packets is controlled by timer, therefore delivery ratio increases owing to less collision in packet forwarding. Throughput for transmission ranges 0.2m, 0.1m, and 0.05m is presented in Fig. 5.9(a), Fig. 5.9(b), and Fig. 5.9(c). Throughput in hierarchical AODV with ACK packet demonstrates better outcome due to the increase in delivery ratio. Fig. 5.10(a), Fig. 5.10(b), and Fig. 5.10(c) illustrate the average end-to-end delay for different transmission range. Here, our modified UDP exhibits slight higher end-to-end delay than hierarchical AODV due to the notion of timer in packet transmitting.

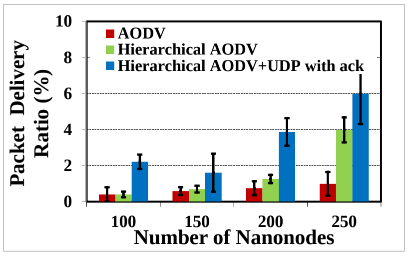
Energy consumption is observed in Fig. 5.11(a), Fig. 5.11(b), and Fig. 5.11(c) for different transmission range. The energy consumption of hierarchical AODV and hierarchical AODV with ACK packet indicate similar result since the packet forwarding is reduced in both mechanisms. Fig. 5.12(a), Fig. 5.12(b), and Fig. 5.12(c) present comparison of the packet drop. Since less number of packet is dropped, hierarchical AODV and hierarchical AODV with ACK packet exhibit significantly better performance. Energy consumption per bit is depicted in Fig. 5.13(a), Fig. 5.13(b), and Fig. 5.13(c). These figures demonstrate that hierarchical AODV with conventional UDP and with our modified UDP perform far better than classical AODV. In the modified UDP, packet flow is controlled by ACK packet and a timer, therefore number of packet forwards is diminished and less energy is consumed. Finally, our analysis reveals the efficiency of our modified UDP in terms of throughput and delivery ratio over conventional



(a) Tx range of nanonodes is 0.2m

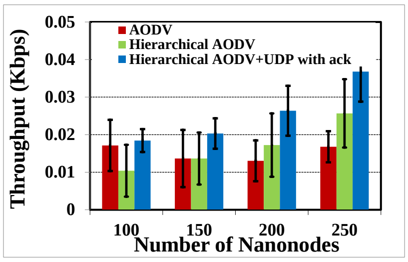


(b) Tx range of nanonodes is 0.1m

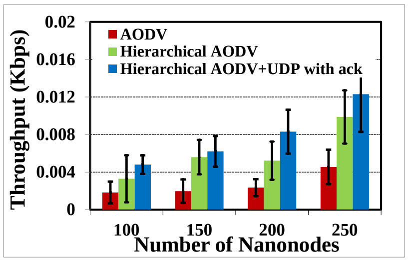


(c) Tx range of nanonodes is 0.05m

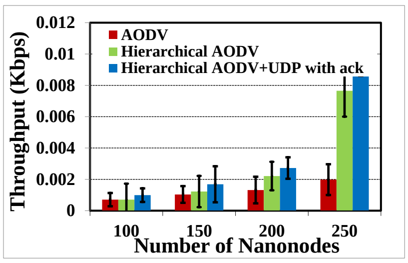
Figure 5.8: Comparison of packet delivery ratio while using 802.15.4 in the MAC layer



(a) Tx range of nanonodes is 0.2m

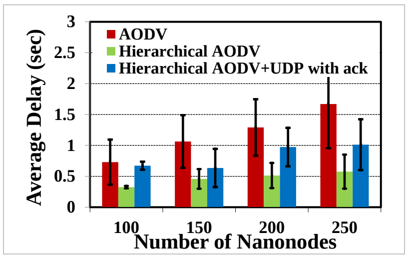


(b) Tx range of nanonodes is 0.1m

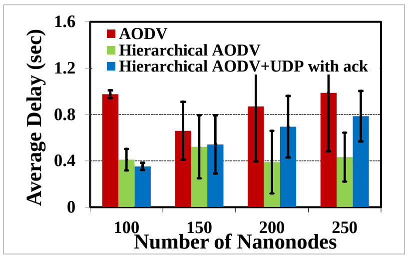


(c) Tx range of nanonodes is 0.05m

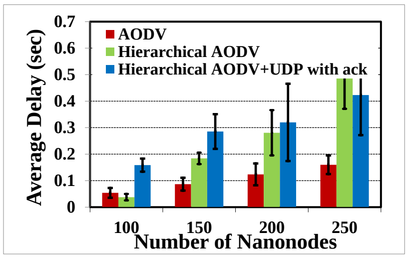
Figure 5.9: Comparison of throughput while using 802.15.4 in the MAC layer



(a) Tx range of nanonodes is 0.2m

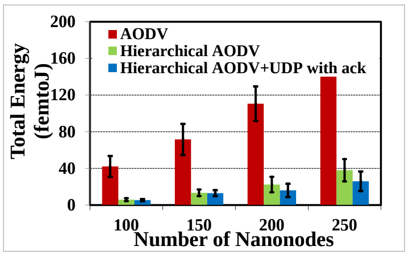


(b) Tx range of nanonodes is 0.1m

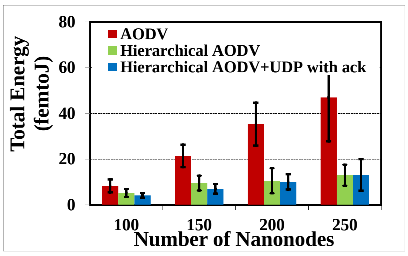


(c) Tx range of nanonodes is 0.05m

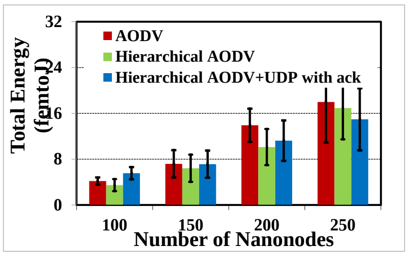
Figure 5.10: Comparison of end-to-end delay while using 802.15.4 in the MAC layer



(a) Tx range of nanonodes is 0.2m

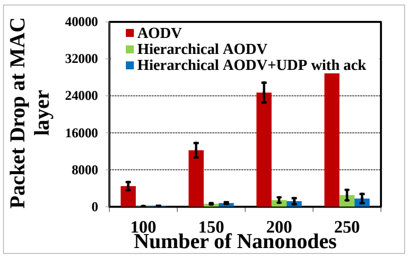


(b) Tx range of nanonodes is 0.1m

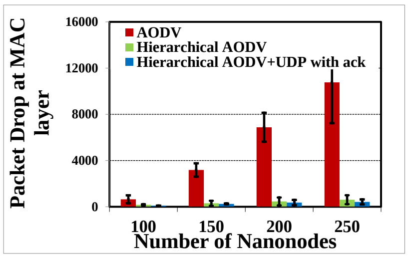


(c) Tx range of nanonodes is 0.05m

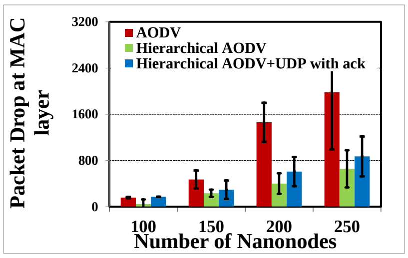
Figure 5.11: Comparison of energy consumption while using 802.15.4 in the MAC layer



(a) Tx range of nanonodes is 0.2m

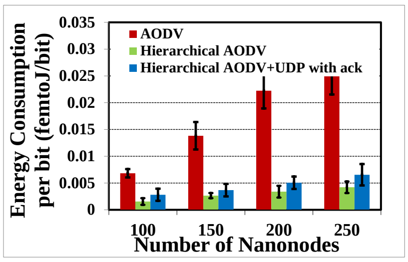


(b) Tx range of nanonodes is 0.1m

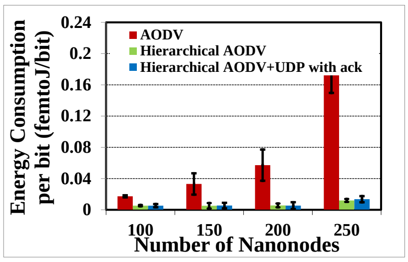


(c) Tx range of nanonodes is 0.05m

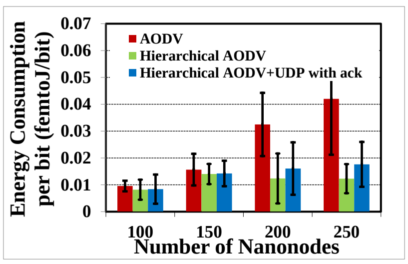
Figure 5.12: Comparison of packet drop while using 802.15.4 in the MAC layer



(a) Tx range of nanonodes is 0.2m

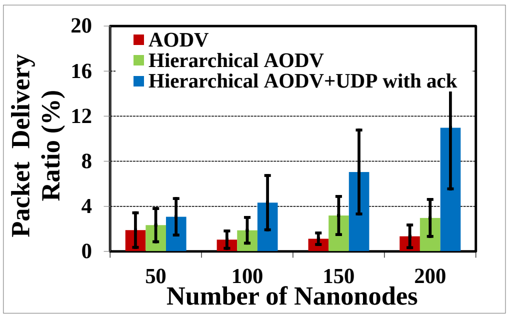


(b) Tx range of nanonodes is 0.1m

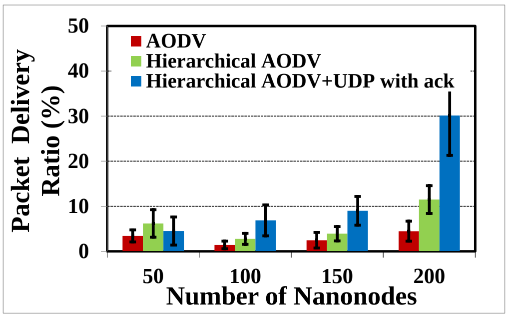


(c) Tx range of nanonodes is 0.05m

Figure 5.13: Comparison of energy per bit while using 802.15.4 in the MAC layer



(a) Random topology



(b) Grid topology

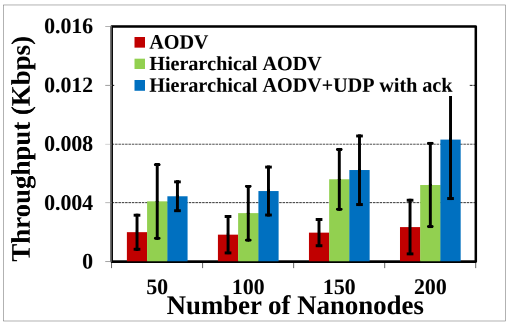
Figure 5.14: Comparison of packet delivery ratio in grid and random topolog

UDP.

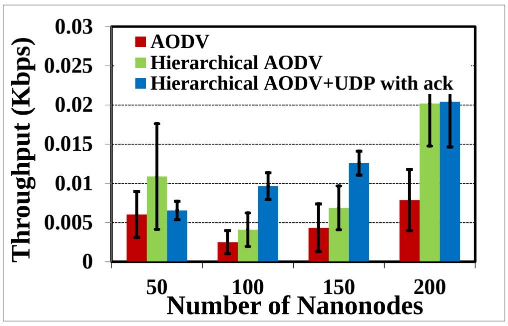
5.2.2 Analysis in Grid Topology

We further perform our simulation in grid topology to compare the performance of the random topology with grid topology in terms of different network parameters. Only nanorouters are placed into grid closer to each other to enable multi-hop path to nanonodes. Nanonodes are deployed randomly over the whole coverage area. We only perform simulation for 0.1m transmission range of nanonodes using the MAC layer protocol 802.15.4. We compare grid and random topology with respect to packet delivery ratio, throughput, end-to-end delay, energy consumption, packet drop and energy consumption per bit adopting AODV, hierarchical AODV and hierarchical AODV with ACK packet. Fig. 5.14(a) and Fig. 5.14(b) show the impact of packet delivery ratio in random and grid topology separately. Since nanorouters are placed in grid, therefore grid topology exhibits better performance compared to random topology. Throughput in these two topology is depicted in Fig. 5.15(a) and Fig. 5.15(b). Throughput is also higher in grid topology due to the increase in delivery ratio.

Fig. 5.16(a) and Fig. 5.16(b) depict end-to-end delay. End-to-end delay for hierarchical AODV and hierarchical AODV with ACK packet show similar trends in both topology. Fig. 5.17(a) and Fig. 5.17(b) illustrate energy consumption for both topology. However, energy consumption in grid topology is higher since most of the nanorouters take part in packet forwarding, therefore more energy is consumed. Fig. 5.18(a) and Fig. 5.18(b) depict the com-

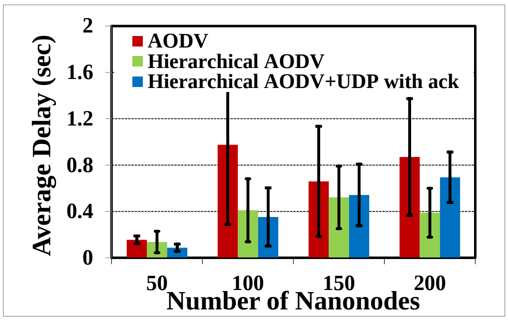


(a) Random topology

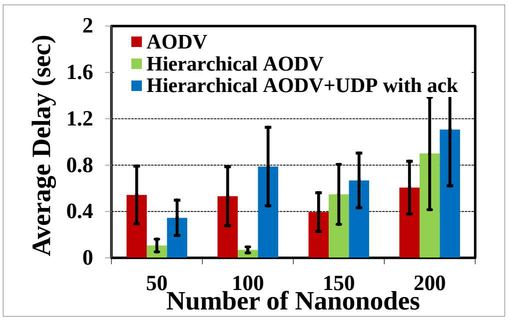


(b) Grid topology

Figure 5.15: Comparison of throughput in grid and random topolog

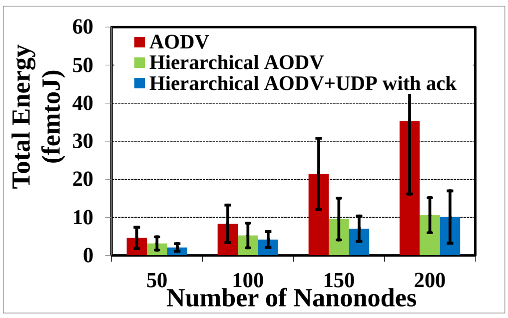


(a) Random topology

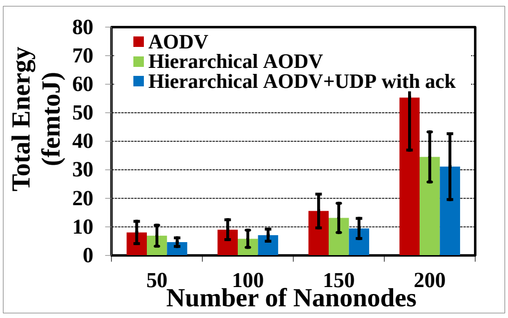


(b) Grid topology

Figure 5.16: Comparison of end-to-end delay in grid and random topolog

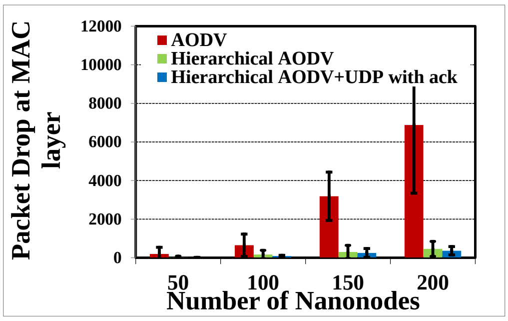


(a) Random topology

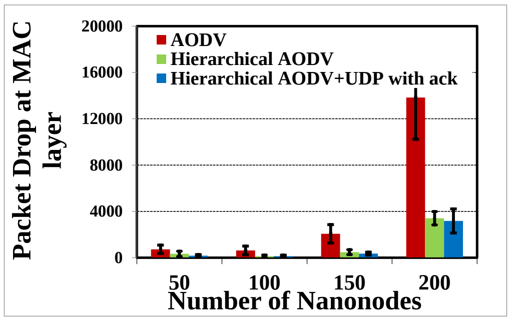


(b) Grid topology

Figure 5.17: Comparison of energy consumption in grid and random topolog

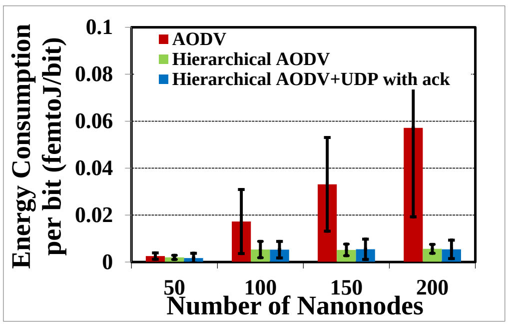


(a) Random topology

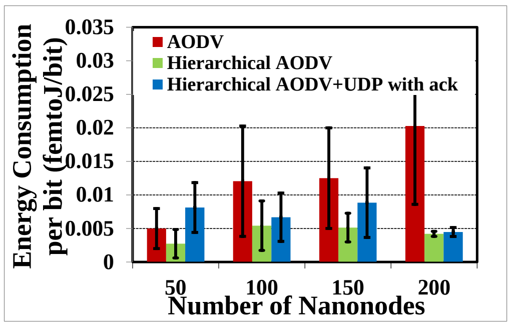


(b) Grid topology

Figure 5.18: Comparison of packet drop in grid and random topolog



(a) Random topology



(b) Grid topology

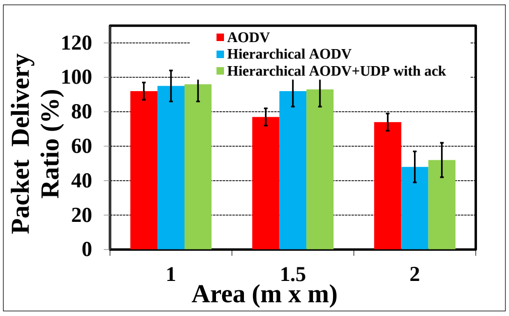
Figure 5.19: Comparison of energy per bit in grid and random topolog

parison of random and grid topology with regard to the packet drop. Number of packet drop is high in grid topology due to the increase in number of forwards made by the nanorouters. Since nanorouters are placed in grid closely to each other, packets are forwarded by one nanorouter to all the nanorouter around it. Energy consumption per bit is demonstrated by Fig. 5.19(a)a and Fig. 5.19(b). Energy per bit in grid and random topology exhibits similar results. Considering all the consequences in grid and random topology, our analysis explores that grid topology performs better than random topology only in terms of delivery ratio and throughput.

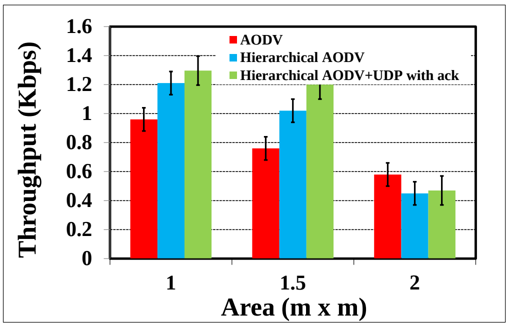
5.2.3 Variation in Simulation Area

We perform ou simulation varying the simulation area. We consider simulation area 1m×1m and 1.5m×1.5m along with 2m×2m. The simulation results are illustrated in Fig. 5.20. Fig. 5.20(a) shows the packet delivery ratio for different areas. As we can see, the packet delivery ratio is higher when the area is smaller for our proposed protocol. Throughput in Fig. 5.20(b) exhibits similar pattern like packet delivery ratio. Fig. 5.20(c) demonstrate the end-to-end delay. End-to-end delay decrease with a decrease in area. Energy consumption is shown in Fig. 5.20(d). Energy consumption is lower for large area since, for large area, packet delivery ratio decreases, therefore, energy consumption decrease due to lower reception and transmission of packets. Packet drop at MAC layer is illustrated in Fig. 5.20(e), where, it is observed that, packet drop for our proposed protocol is very lower the traditional AODV.

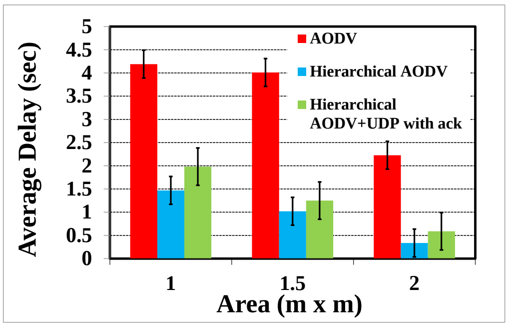
Our perform analysis on dense deployments explores the efficacy and efficiency of our proposed protocols. In dense deployment, packet delivery ratio is higher. The packet delivery ratio is almost 100%. In dense deployment, the nodes are placed closely. Hence, the routing path for data delivery are discovered easily as in most cases each node finds a neighbor within its transmission range. Therefore, the routing path is discovered efficiently. As the packet delivery ratio is higher, the throughput is also higher. End-to-end delay is very lower since the routing path is found from source to destination more quickly because of the close proximity of the nodes.



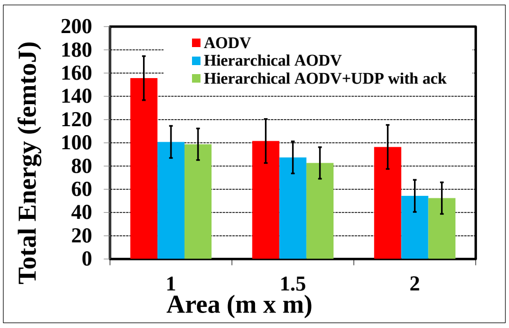
(a) Packet delivery ratio



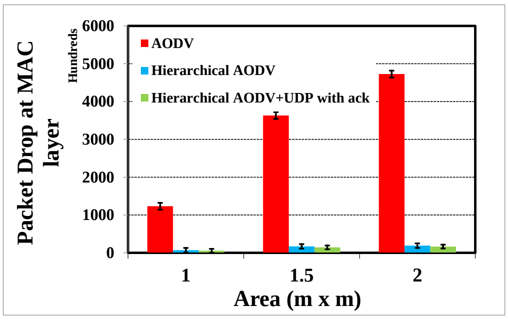
(b) Throughput



(c) Average end-to-end delay



(d) Total energy consumption

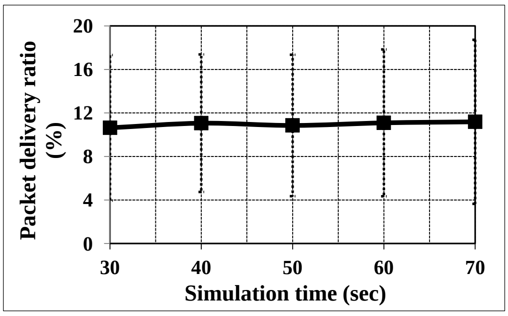


(e) Packet drop at MAC layer

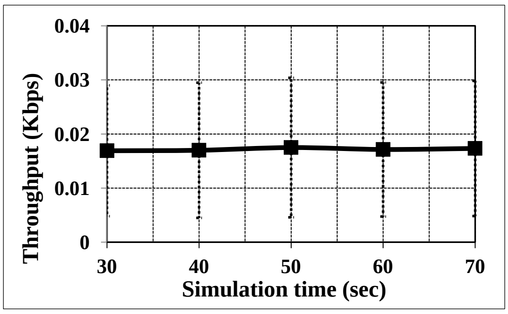
Figure 5.20: Variation in simulation area on different performance metrics

5.2.4 Variation in Simulation time

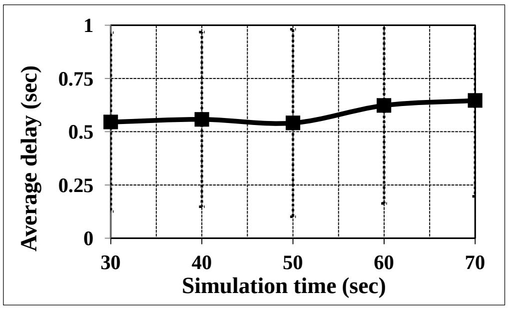
We perform our simulation of WNSNs in response to varying the simulation time. Fig. 5.21(a), 5.21(b), 5.21(c), 5.21(d), and 5.21(e) illustrate the impact of variation in simulation time on



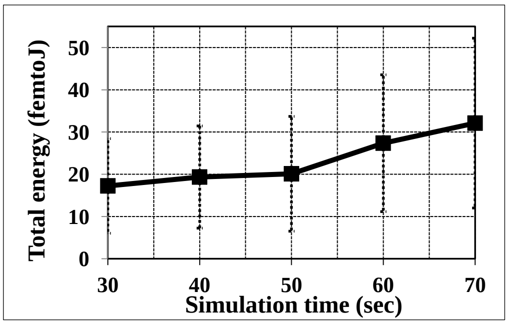
(a) Packet delivery ratio



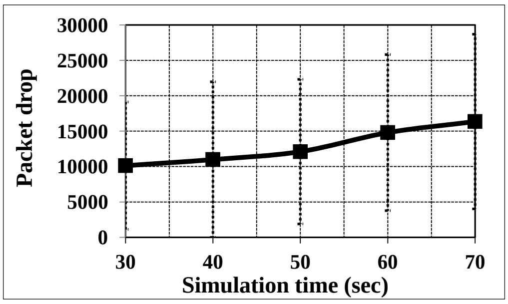
(b) Throughput



(c) Average end-to-end delay



(d) Total energy consumption



(e) Packet drop at MAC layer

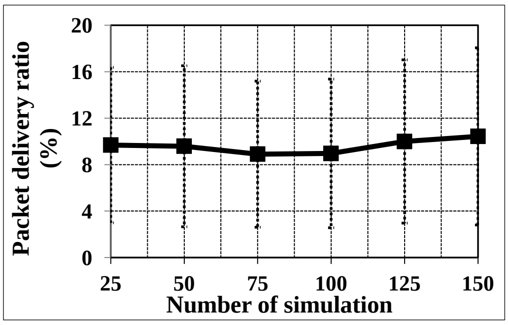
Figure 5.21: Variation in simulation time on different performance metrics

different performance metrics. Here, we use AODV for routing protocol and MAC 802.11 as MAC layer protocol. We conduct simulation for 100 nanonodes each having transmission distance 0.1m. We use UDP as the Transport layer protocol. We have performed all our simulation for 50 sec previously, hence we vary the simulation time as 30, 40, 50, 60, and 70 sec. Fig. 5.21(a) demonstrate packet delivery ratio for 30, 40, 50, 60, and 70 sec simulation time. Delivery ratio remains almost same for each simulation time. Average throughput for different simulation time is presented in Fig. 5.21(b). Here, throughput also remain almost fixed for different simulation time. Throughput does not change as packet delivery ratio remain fixed. Fig. 5.21(c) shows the average end-to-end delay for different simulation time. End-to-end delay demonstrate slight increase for simulation time 60 and 70 sec.

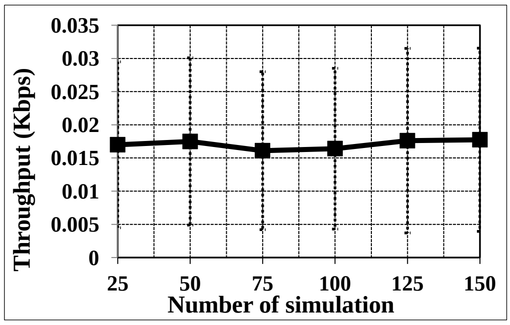
Fig. 5.21(d) exhibit total energy consumption for different simulation time. Energy consumption also increases with an increase in simulation time. When simulation time gets larger, more packets are generated. Nano devices send and receive more packets, and thus consume more energy. Hence, the energy consumption of whole network increase when simulation time increases. Variation in simulation time on packet drop is illustrated in Fig. 5.21(e). The number of packet drop increases with an increase in simulation time. This happens because for larger simulation time, more packets are generated and more packets are tend to drop.

5.2.5 Variation in Number of Simulations

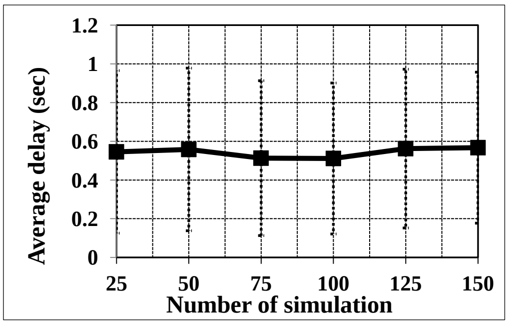
We further conduct our simulation of WNSNs in response to varying the number of simulation to determine the compact value of standard deviation. As, we consider all the nano devices are deployed randomly, hence the values of different performance metrics exhibit much deviation. Values of performance metrics vary a lot per simulation, hence the standard deviation is larger. We perform our simulation 50 times previously and we have taken the average value of 50 simulations. To gain insight the impact of number of simulation on standard deviation, we conduct simulation 25, 50, 75, 100, 125, and 150 times. We compute different performance metrics for each set of simulation. Fig. 5.22 illustrate the impact of variation in number of simulation on packet delivery ratio, throughput, end-to-end delay, total energy, and packet drop. Here, we use AODV for routing protocol and MAC 802.11 as MAC layer protocol. We conduct simulation for 100 nanonodes each having transmission distance 0.1m. We use UDP as



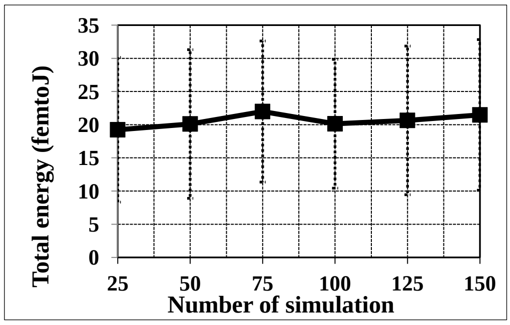
(a) Packet delivery ratio



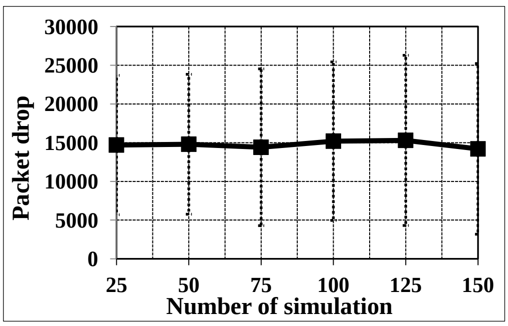
(b) Throughput



(c) Average end-to-end delay



(d) Total energy consumption



(e) Packet drop at MAC layer

Figure 5.22: Variation in number of simulation on different performance metrics

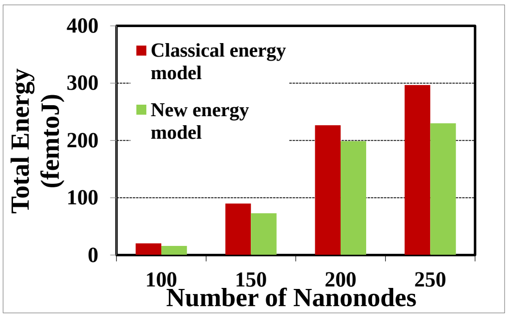
the Transport layer protocol. Here, Fig. 5.22(a) demonstrate linear pattern in packet delivery ratio. The average values of packet delivery ratio remain quite same for each set of simulations. The values for 125 and 150 simulation are slight larger. The standard deviation remain almost same for all set of simulations.

Throughput is illustrated by Fig. 5.22(b). Throughput also exhibits same trend like packet delivery ratio. End-to-end delay is demonstrated in Fig. 5.22(c). End-to-end delay also shows similar trend for different number of simulations. Fig. 5.22(d) exhibit total energy consumption for different number of simulation. Energy consumption shows similar trend for all the number of simulations. Variation in number of simulation on packet drop is illustrated in Fig. 5.22(e). The number of packet drop remain almost same for 25, 50, 75, 100, 125, and 150 number of simulations.

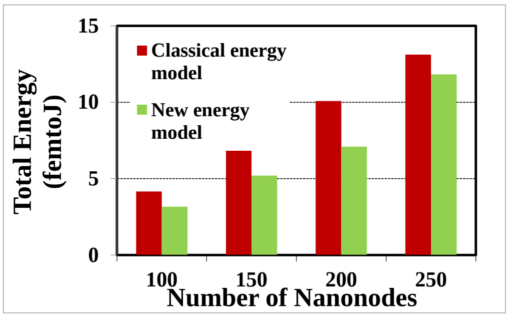
5.2.6 New Energy Model

So far we have simulated our proposed wireless nanosensor network using the classical energy model for sensors. Several existing studies [11, 77] focus on energy harvesting and energy model design for nanonetwork. In [11], the authors propose a handshake-based MAC protocol, namely the PHLAME, which is designed on top of a modulation scheme called RD TS-OOK (Rate Division Time Spread On-Off Keying. The Rate Division Time Spread On-Off Keying (RD TS-OOK) is considered as a modulation scheme in nano-communication. A logical "1" is transmitted as a femtosecond-long pulse and a logical "0" is encoded as silence.

We have implemented energy model based on this modulation scheme. As we have calculated energy for sending only 1's in data which supports this modulation scheme. We incorporated this energy model in `ns-2`. Fig. 5.23(a) and 5.23(b) demonstrate the comparison of classical energy model and new energy model. Here, we use our proposed hierarchical AODV for routing protocol and MAC 802.11 and MAC 802.15.4 as MAC layer protocol. We conduct simulation for nanonodes each having transmission distance 0.1m. We use UDP as the Transport layer protocol. Here, Fig. 5.23(a) shows total energy consumption for MAC layer 802.11. As we can see, the energy consumption significantly decreases for the new energy model. Reason behind this decrements is when only 1 is sent as data in data packet without the 0's, then the size of data packet gets decreased. Hence, total energy consumption decreases



(a) Energy consumption while using MAC layer protocol 802.11



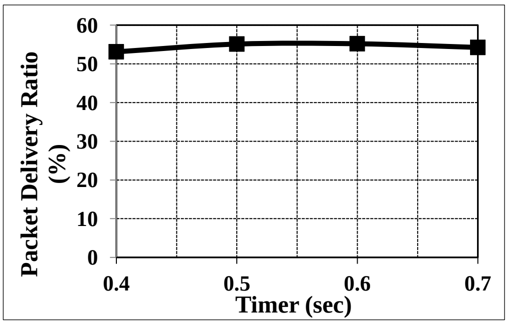
(b) Energy consumption while using MAC layer protocol 802.15.4

Figure 5.23: Comparison of energy consumption

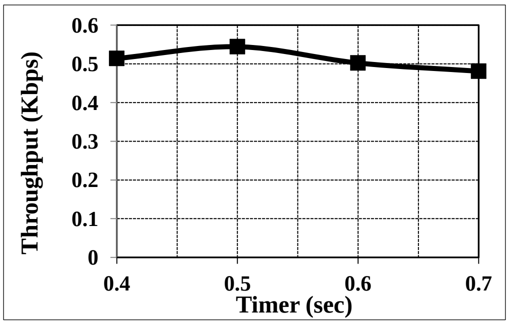
remarkably. Fig. 5.23(b) shows similar pattern as Fig. 5.23(a) for energy consumption. Here, MAC layer protocol 802.15.4 is used and total energy consumption is computed using the new energy model.

5.2.7 Variation in Transmission Control Timer

We also vary the timer value in our proposed Transport layer protocol and conduct simulation. Fig. 5.24 shows the packet delivery ratio and throughput for different values of timer. From Fig. 5.24(a), we can observe that the packet delivery ratio remain fixed for different values of



(a) Packet delivery ratio



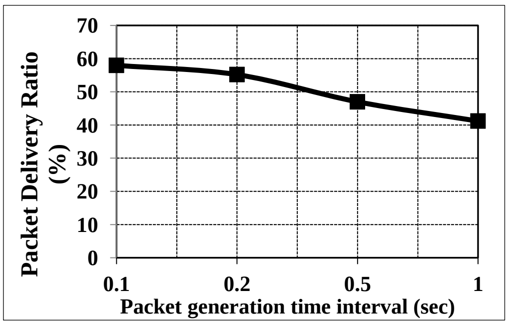
(b) Network Throughput

Figure 5.24: timer

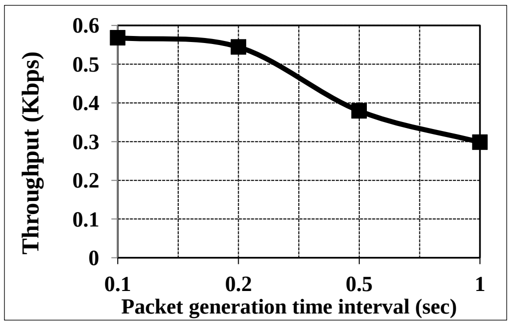
timer. Hence, throughput also exhibit similar trend in Fig. 5.24(b).

5.2.8 Variation in Transmission rate

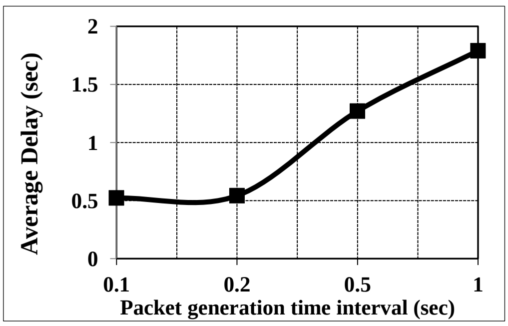
We vary the transmission rate to analyze the performance of different network metrics. Fig. 5.25 demonstrate the different performance metrics for the different packet generation interval. We consider 0.1, 0.2, 0.5 and 1 second time interval of packet generation and simulate different performance metrics. Fig. 5.25(a) illustrate packet delivery ratio for different transmission rate. The packet delivery ratio decreases with a decrease in transmission rate. Throughput in Fig. 5.25(b) also exhibit similar behavior. Average end-to-end delay is shown by the Fig. 5.25(c) where the end-to-end delay significantly increases when transmission rate decreases. Total energy consumption of the network is shown in Fig. 5.25(d). Energy consumption



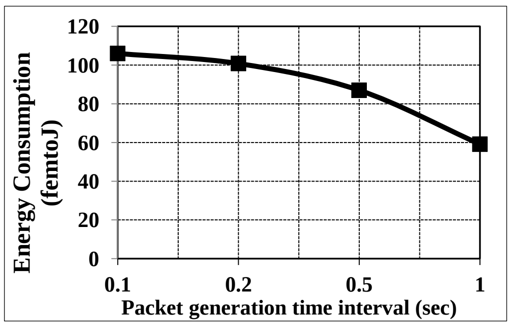
(a) Packet delivery ratio



(b) Throughput



(c) Average end-to-end delay



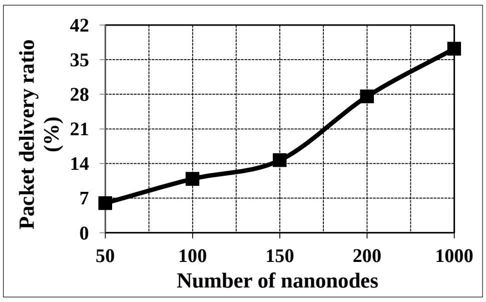
(d) Total energy consumption

Figure 5.25: Variation in transmission rate on different performance metrics

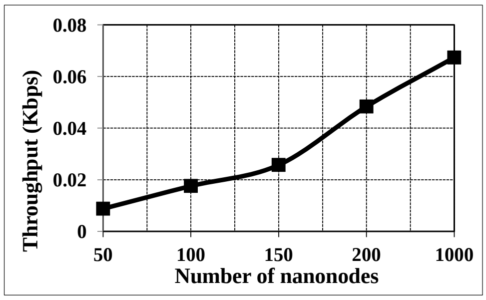
decreases with decreasing transmission rate, because for lower packet transmission rate, packet generation gets lower, hence less energy is consumed.

5.2.9 Simulation in Large-scale Scenario

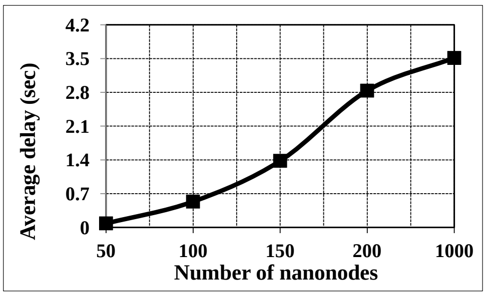
We perform simulation for large-scale scenario. We consider 1000 number of nanonodes for our simulation. Here, we use AODV for routing protocol and MAC 802.11 MAC layer protocol. Fig. 5.26(a), 5.26(b), 5.26(c), 5.26(e), and 5.26(d) compare the different performance metrics for 1000 nanonodese with 50, 100, 150, and 200 nanonodes. Fig. 5.26(a) shows packet delivery ratio 1000 nanonodes. As the packet delivery ratio increases when the number of nanonodes is larger as 1000 nanonodes. Fig. 5.26(b) compares throughput for 1000 nanonodes with other variation in number of nanonodes. Throughput also gets increased for a large number of nanonodes. End-to-end delay is illustrated in Fig. 5.26(c) where the delay also augment when the number of nanonodes gets larger. Fig. 5.26(e) shows total energy consumption for 1000 nanonodes. Total energy consumption increases for large number of nanonodes. This happens because when number of nanonodes gets very larger, more packets are generated and the number of packet transmission and reception also raise. Therefore, the total energy consumption of the overall network increases. Finally, Fig. 5.26(d) shows the packet drop for 1000 number of nanonodes. Packet drop drastically increases for 1000 number of nanonodes. More packets are produced due to large number of nanonodes. Hence, more packets are dropped in overall network.



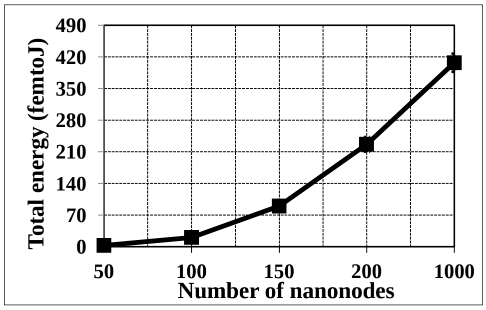
(a) Packet delivery ratio



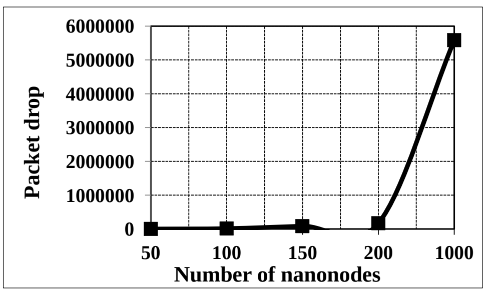
(b) Throughput



(c) Average end-to-end delay



(d) Total energy consumption



(e) Packet drop at MAC layer

Figure 5.26: Performance in large-scale scenario

5.3 Simulation Findings

We also compare the performance of our proposed protocols with some existing protocols proposed in [1] and [78] along with AODV, DSR, and DSDV. In [1], the authors propose two routing protocols for WNSN namely flooding and random routing. In flooding, the packet are broadcasted to all the neighbors within the transmission range of a nano device. In random routing, one nano device select a neighbor randomly from its all neighbor to forward the packet. An energy efficient cross Layer routing protocol with adaptive dynamic retransmission for wireless sensor Networks is proposed in [78]. Here, to achieve prolonged network lifetime while considering overall energy consumption in the wireless network. In this paper, efficient cross layer routing protocol (EECLP) is introduced which is designed to adopt cross-layer strategy where the amount of energy consumed is considered during routing from one node to another for wireless sensor networks. When a node wants to send data to a destination, the routing path is determined based on minimum consumed energy. The path consisting of nodes which have maximum energy are chosen as the route from source to destination. We implement this protocol in `ns-2`. We compare the performance metrics of our proposed protocols with these existing protocol flooding, random routing and EECLP. As the random routing exhibit very poor values with respect to all the performance matrix, we are not showing the comparison with random routing. The percentage of improvement of our proposed protocol with respect to flooding and EECLP is shown in Table 5.2, 5.4, 5.5, and 5.6.

In Table 5.2, the percentage of improvement in performance with hierarchical AODV using MAC layer protocol 802.11 is shown. Here, our proposed protocol in Network layer perform far better than EECLP with respect to throughput. The percentage of improvement in throughput with respect to EECLP is much higher for all the transmission ranges. However, the percentage of improvement in throughput with respect to flooding is well only for 0.05 transmission ranges. End-to-end delay in our proposed protocol perform well than flooding. However, EECLP exhibit better performance in end-to-end delay. This happens because EECLP randomly choose neighbor and do not broadcast the packets. Hence, end-to-end delay becomes lower. The total energy consumption is better in our proposed protocol than flooding. Energy per bit for our proposed protocol demonstrates better performance than both flooding and EECLP. Table 5.4 illustrate the percentage of improvement in performance with hierarchical AODV and ACK-based UDP using MAC layer protocol 802.11. Here, the percentage of improvement in performance metrics shows similar pattern like Table 5.2.

In Table 5.5, the percentage of improvement in performance metrics such as throughput, end-to-end delay, energy consumption, energy consumption per bit with hierarchical AODV using MAC layer protocol 802.15.4 is shown. Here, our proposed protocol in Network layer exhibits significantly better performance than flooding EECLP with respect to throughput. The percentage of improvement in throughput with respect to EECLP and flooding is much higher for all the transmission ranges. End-to-end delay in our proposed protocol perform well than flooding. However, EECLP exhibit better performance in end-to-end delay. The total energy consumption is better in our proposed protocol than flooding. EECLP consumes less energy because here the routing path is decided by selecting specific neighbor without broadcasting the packets. Energy per bit for our proposed protocol demonstrates better performance than both flooding and EECLP. Table 5.4 illustrate the percentage of improvement in performance with hierarchical AODV and ACK-based UDP using MAC layer protocol 802.15.4. Here, the percentage of improvement in performance metrics shows similar pattern like Table 5.2.

Table 5.2, 5.4, 5.5, 5.6, 5.3, and 5.7 summarize the percentage of improvement with respecct to different network metrics using our proposed methodologies. Here, we review key findings obtained from our simulation studying the different network parameters.

- The network behavior of WNSNs varies with different ad-hoc routing protocols. Different network parameters such as throughput, end-to-end delay, energy consumption, energy consumption per bit, delivery ratio, and packet drop for WNSNs exhibit variations after adopting different routing protocols. From our simulation, we explore that AODV perform better compared to other routing protocols in response to these parameters.

- Our proposed hierarchical AODV performs better than classical AODV. Average end-to-end delay, energy consumption, energy consumption per bit and packet drop significantly reduce with hierarchical AODV.

- Different MAC alternatives exhibit different results. MAC 802.11 performs better than MAC 802.15.4 in WNSNs in terms of delivery ratio and throughput. However, 802.15.4 shows better results in performance metrics such as energy consumption, energy consumption per bit, average end-to-end delay, and packet drop.

Table 5.2: Percentages of performance improvement using our proposed methodologies

Transmission range (m)	Number of nano-nodes	Percentage of improvement in performance using hierarchical AODV with MAC layer protocol 802.11							
		Through-put w.r.t.		End-to-end delay w.r.t.		Energy consumption w.r.t.		Energy per bit w.r.t.	
		flooding	EECLP	flooding	EECLP	flooding	EECLP	flooding	EECLP
0.05	100	41	370	92	-108	28	-94	51	98
	150	81	1917	60	-25	33	-110	52	100
	200	24	6096	51	-52	63	-129	69	100
	250	89	8092	30	-63	88	-135	76	99
0.1	100	-50	1723	90	-82	80	-49	37	99
	150	9	5323	74	-190	81	-89	83	100
	200	18	1189	81	-32	83	-190	93	100
	250	32	2387	87	-22	89	-98	96	100
0.2	100	-77	2187	77	-71	95	-41	61	100
	150	-62	4157	86	-10	85	-86	60	100
	200	-53	4545	87	-58	88	-87	72	100
	250	-55	6618	98	-66	90	-89	86	99
	Average	17	2551	70	-72	70	-87	66	99

- Our proposed acknowledgement-based UDP with hierarchical AODV performs better with 802.15.4 and achieves higher packet delivery ratio, and throughput having almost similar pattern for energy consumption, energy consumption per bit and packet drop as hierarchical AODV.

Table 5.3: Percentages of performance improvement using our proposed methodologies

Transmission range (m)	Number of nano-nodes	Percentage of improvement in performance using hierarchical AODV with MAC layer protocol 802.11											
		Throughput w.r.t.		End-to-end delay w.r.t.		Energy consumption w.r.t.		Packet delivery ratio w.r.t.		Packet drop w.r.t.		Energy per bit w.r.t.	
		AODV	DSR	AODV	DSR	AODV	DSR	AODV	DSR	AODV	DSR	AODV	DSR
0.05	100	2	130	85	92	10	48	2	2	25	21	42	77
	150	-27	163	45	32	27	40	-27	16	61	55	-25	72
	200	-30	57	26	22	55	82	-21	-24	80	86	40	90
	250	-35	69	37	28	65	89	-16	-19	84	89	42	91
0.1	100	-45	-50	87	88	69	88	-58	-54	93	94	26	88
	150	7	-18	68	45	78	91	2	-32	93	93	78	95
	200	15	-2	78	83	80	89	9	-9	92	93	92	94
	250	22	-3	85	89	83	90	11	-5	94	93	94	96
0.2	100	-78	-78	73	-237	92	84	-73	-73	98	94	53	56
	150	-64	-65	82	-78	84	71	-64	-64	95	85	54	63
	200	-55	-56	84	-83	86	76	-49	-49	95	89	67	74
	250	-45	-46	89	-72	90	81	-46	-46	98	90	73	78
	Average	-35	12	57	9	59	75	40	79	81	84	65	76

Table 5.4: Percentages of performance improvement using our proposed methodologies

Trans-mission range (m)	Number of nano-nodes	Percentage oof improvement in performance using hierarchical AODV and ack based UDPwith MAC layer protocol 802.11							
		Through-put w.r.t.		End-to-end delay w.r.t.		Energy consumption w.r.t.		Energy per bit w.r.t.	
		flooding	EECLP	flooding	EECLP	flooding	EECLP	flooding	EECLP
0.05	100	50	200	32	-16	35	-98	49	72
	150	88	2309	23	-5	33	-104	39	88
	200	45	6209	44	-8	63	-130	54	100
	250	36	9543	56	-4	78	-145	65	100
0.1	100	-30	1832	57	-42	75	-54	29	91
	150	11	5492	55	-34	77	-93	48	75
	200	22	1302	45	-11	83	-148	65	83
	250	34	2678	38	-6	89	-155	74	87
0.2	100	-69	2213	34	-7	67	-56	53	98
	150	-56	4298	56	-8	81	-92	52	87
	200	-49	4609	45	-15	74	-82	69	89
	250	-34	8375	62	-12	81	-78	73	93
	Average	12	2647	44	-14	63	-85	45	87

Table 5.5: Percentages of performance improvement using our proposed methodologies

Transmission range (m)	Number of nano-nodes	Percentage of improvement in performance using hierarchical AODV with MAC layer protocol 802.15.4							
		Through-put w.r.t.		End-to-end delay w.r.t.		Energy consumption w.r.t.		Energy per bit w.r.t.	
		flooding	EECLP	flooding	EECLP	flooding	EECLP	flooding	EECLP
0.05	100	22	499	42	-12	32	-67	62	76
	150	22	2973	-45	-4	21	-89	29	81
	200	100	6485	-56	-5	29	-99	61	87
	250	133	9864	-61	-4	32	-105	68	89
0.1	100	64	3116	59	-7	52	-62	60	95
	150	156	7813	32	-5	65	-58	83	85
	200	79	4738	59	-8	75	-97	84	83
	200	98	9874	64	-5	81	-103	88	90
0.2	100	-38	1276	64	-9	88	-43	79	67
	150	8	1405	72	-14	84	-58	83	76
	200	29	342	71	-12	82	-74	85	76
	250	44	568	78	-10	80	-81	89	82
	Average	43	2545	35	-8	55	-67	69	80

Table 5.6: Percentages of performance improvement using our proposed methodologies

Transmission range (m)	Number of nano-nodes	Percentage of improvement in performance using hierarchical AODV and ACK-based UDP with MAC layer protocol 802.15.4							
		Through-put w.r.t.		End-to-end delay w.r.t.		Energy consumption w.r.t.		Energy per bit w.r.t.	
		flooding	EECLP	flooding	EECLP	flooding	EECLP	flooding	EECLP
0.05	100	37	841	31	34	17	-74	29	56
	150	34	3488	-11	-10	12	-99	31	69
	200	167	7131	-23	-12	19	-110	73	73
	250	193	11928	-28	-8	27	-119	79	80
0.1	100	89	4109	34	-21	37	-71	54	75
	150	172	8278	27	-23	45	-65	78	81
	200	120	5442	43	-27	56	-105	65	67
	250	160	9837	56	-32	62	-109	75	78
0.2	100	11	1568	45	-11	65	-54	39	54
	150	24	1890	67	-19	57	-63	46	57
	200	37	567	756	-22	61	-81	54	35
	250	45	1184	283	-31	68	-87	65	47
	Average	71	2988	87	-14	38	-76	49	60

Table 5.7: Percentages of performance improvement using our proposed methodologies

Transmission range (m)	Number of nano-nodes	Percentage of improvement in performance using hierarchical AODV with ACK based UDP with MAC layer protocol 802.15.4											
		Throughput w.r.t.		End-to-end delay w.r.t.		Energy consumption w.r.t.		Packet delivery ratio w.r.t.		Packet drop w.r.t.		Energy per bit w.r.t.	
		AODV	Hierarchical AODV	AODV	Hierarchical AODV	AODV	Hierarchical AODV	AODV	Hierarchical AODV	AODV	Hierarchical AODV	AODV	Hierarchical AODV
0.05	100	40	40	-194	-320	-32	-59	451	451	-8	-262	12	-2
	150	62	37	-228	-54	1	-11	172	130	37	-25	9	-1
	200	106	23	-158	-13	19	-11	416	207	58	-51	50	-29
	250	122	25	-108	-11	31	-9	478	299	63	-48	59	-31
0.1	100	161	45	63	14	49	20	314	130	86	46	69	1
	150	214	11	17	-4	67	26	526	121	92	17	1	-5
	200	253	59	20	-78	71	4	719	269	94	21	90	4
	250	311	65	29	-67	83	13	865	345	123	34	94	7
0.2	100	7	77	7	-106	87	8	6	74	96	-70	88	-19
	150	48	48	40	-38	81	3	131	131	93	-24	89	-11
	200	102	53	24	-89	85	28	175	108	95	16	91	-27
	250	156	65	35	-78	89	37	2345	124	99	23	98	-21
	Average	95	44	-41	-69	49	7	52	-5	85	-18	45	-9

5.4 Discussion and Analysis

Summarizing our contributions, we evaluate the network-level performance of WNSNs using classical MAC and Network layer protocols considering real antenna behavior. We propose a hierarchical AODV routing protocol in the Network layer and acknowledgement-based UDP protocol in the Transport layer to enhance the network-level performance of WNSNs. We also vary several network parameters and analyze the performance of our proposed protocol for different variation. In this section, we will discuss the performance of our proposed solution for different variations of network parameters.

- We evaluate the performance of WNSNs using AODV, DSR, and DSDV routing protocol with MAC 802.11 for random topology. Here, packet delivery ratio, and throughput are higher with DSR, however, other metrics such as average end-to-end delay, energy consumption, energy consumption per bit, and packet drop are lower with AODV. Therefore, AODV perform better for WNSNs considering overall network-level performance.

- Our proposed hierarchical AODV routing protocol improve the performance of WNSNs in terms of average end-to-end delay, energy consumption, energy consumption per bit, and packet drop compared to classical AODV and DSR. It also exhibits similar performance in terms of throughput and packet delivery ratio compared to AODV and DSR.

- While using MAC 802.15.4, hierarchical AODV performs better than AODV, DSDV, and DSR. However, the packet delivery ratio and throughput decrease drastically for MAC 802.15.2. Here, our proposed acknowledgement-based UDP protocol at the Transport layer enhances the performance in terms of throughput and packet delivery ratio keeping other metrics such as average end-to-end delay, energy consumption, energy consumption per bit, and packet drop almost same like hierarchical AODV.

- We evaluate the performance of WNSNs for different transmission ranges of nanonodes such as 0.05m, 0.1m, and 0.2m considering random topology. For 0.2m transmission range, the packet delivery ratio and throughput are significantly higher with our proposed solution. However, for 0.05m transmission range, throughput and packet delivery ratio are very lower.

- We also analyze performance for grid topology using our proposed protocols. Packet delivery ratio and throughput are higher compared to random topology. However, average end-to-end delay, energy consumption, energy consumption per bit, and packet drop exhibit poor performance in grid topology compared to random topology

- We investigate the performance of WNSNs for more dense deployment. In dense deployment, our proposed protocols significantly shows better performance in all network metrics including packet delivery ratio (above 90%), throughput, average end-to-end delay, energy consumption, energy consumption per bit, and packet drop.

- We vary the simulation time and study the performance. Packet delivery ratio remains almost same for different simulation time. Our proposed Network and Transport layers protocols also show almost similar performance for other network metrics.

- We inspect network behavior of WNSNs varying the number of simulation iterations. Here, packet delivery ratio and throughput including all other metrics remain almost same for different number of simulations.

- We implement a new energy model. Our proposed protocols consume much lower energy with the new energy model.

- We vary the transmission control timer for our proposed acknowledgement-based UDP protocol. Here, throughput, packet delivery ratio, and other parameters remain almost fixed for different values of timer.

- We analyze the performance of WNSNs varying the data transmission rate. Packet delivery ratio and throughput decrease with an increase in data transmission rate. Average delay increases with an increase in data transmission rate.

- We also study the performance of WNSNs for large scale scenarios such as for 1000 nanonodes. Throughput, packet delivery ratio, average end-to-end delay, energy consumption, energy consumption per bit, and packet drop increases for 1000item nanonodes using our proposed protocols.

Chapter 6

Conclusion and Future Work

In this thesis work, we summarize our achievements.

- The novelty of our work is we analyze the network-level performance of WNSNs considering multihop routing for different important network metrics for the first time.
- We propose a hierarchical AODV routing protocol in the Network layer to enhance the network-level performance for different metrics of WNSNs. Our proposed protocol confirm efficacy for different metrics which we have shown through `ns-2` simulation.
- We also propose an acknowledgement-based UDP protocol at the Transport layer to control the data transmission rate and thereby improve the network performance of WNSNs. Our `ns-2` simulation also confirms the superioty of our proposed Transport layer protocol.
- We perform `ns-2` simulation to evaluate the performance of WNSNs considering different metrics using classical MAC and Network layer protocols. Afterwards, based on our performance analysis, we propose a new Network and Transport layer protocol to further improve the performance of WNSNs. Our proposed solutions ensure the efficiency for different network parameters which we exhibit through `ns-2` simulation.

Study of network-level behavior of WNSNs adopting classical MAC and routing protocols is little explored in the literature In our work, we first develop a system model for WNSNs considering real nano-antenna behavior along with THz communication for WNSNs. Subsequently, we enable these aspects in the network simulator `ns-2` through performing necessary modifications in the simulator. Afterwards, we analyze the network-level performance of WNSNs through adopting classical ad hoc routing protocols such as AODV, DSDV, and DSR for different transmission ranges, different number of nanosensors, and different MAC alternatives. Next, utilizing results of the performance analysis, we propose new protocols for Network layer and Transport layer with a goal of enhancing network-level performance in ad hoc WNSNs. Finally, we evaluate performance of the newly-proposed protocols and compare with existing protocols over diversified ad hoc WNSN settings in `ns-2`. Our proposed protocols exhibit significant performance improvement for ad hoc WNSN for different network metrics such as throughput, end-to-end delay, energy consumption, energy consumption per bit, packet delivery ratio, packet drop, etc.

In future, we plan to perform performance evaluation of our proposed methodologies using real network settings. We are also studying impact of directional nano-antenna to determine the network behavior of WNSNs. For dense WNSN, overhearing is a major problem. When the nanonodes are deployed densely, they are very likely to overhear the transmission of another node. To address this problem and to mitigate the interference level of WNSN, we are working directional graphene-based nano-antenna design.

In THz communication, a major concern is the molecular absorption of the transmission medium. The molecules in the transmission medium absorb energy from EM waves. It is defined as a molecular absorption. The molecular absorption coefficient is different for different types of molecules. In our future work, we plan to include molecular absorption in the propagation model to determine the transmission behavior for THz communication. We plan to study the impact of other antenna materials for nano-antennas.

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