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4 authors, including:

Najah Abu Ali
Queen's University

Fatiha Djebbar
United Arab Emirates University

Akram Alomainy
Queen Mary, University of London

Evaluation of Data Dissemination Schemes in Electromagnetic Nanosensor Networks

Najah AbuAli[1], Sam Aleyadeh[2], Fatiha Djebbar[1], Akram Alomainy[3]

[1] College of Information, Technology, UAE University, Al-Ain, United Arab Emirates

[2] Electrical Engineering Department, College of Engineering, AlFaisal University, Saudi Arabia

[3] School of Electronic Engineering and Computer Science, Queen Mary University of London, London, UK

***Abstract*—Revolutionary advancement in realizing nano-sensors promises unprecedented enhancement of applications in several fields such as health, industry, agriculture, environment, sport, etc. The small size of nano-sensors and their THz band leads to significant constraints in energy, memory, processing, and transmission range. To combat these constraints, recent progress and active research in nano-sensing technology have led to increasing interest in connecting these nano-sensors in a new network technology, the nano-network. Communication in nano-networks still poses a non-trivial challenge owing to the constraint of processing, storage, energy, and communication range capabilities of nano-nodes. Short communication range in the THz band renders direct communication in nano-networks infeasible most of the time. Hence, multihop communication among nano-nodes is currently regarded as the viable solution for nano-network realization. In this paper, we investigate three routing protocols; controlled flooding, CORONA, and Hierarchical AODV. We evaluate the performance of the three protocols with different transmission ranges and network densities.**

I. Introduction

The significant advancement of nano-technology promoted the exponential rise of nano-technology applications, which is expected to enhance and complement the function of several applications in different fields, such as military, health-care, and industrial manufacturing. This is a natural consequence of the successful realization of nano-sized sensor nodes. Armed with a graphene nano-antenna, processing unit, storage unit, and energy harvesting component, nano-sensors were able to carry out simple tasks. However, these tasks are constrained and limited. This invited collaboration among a large number of sensor nodes to empower these nodes to provide more complex services. Hence, this brought about the advent of new technology; the wireless nano-sensor network and the Internet of nano-things networks. Collaboration among nano-scale nodes to extend the performance of nano-nodes beyond executing simple tasks has become a reality through nano-networks, which hold much greater communication and processing potential than stand alone nano-machines. However, data dissemination in nano-networks poses a nontrivial challenge owing to the constraint of processing, storage, energy, and communication range capabilities of nano-nodes. Short communication range in the THz band along with additional sources of noise such as signal molecular absorption inside the human body compared to the traditional networks render direct communication between nano-sensors and the gateway infeasible most of the time [1]. Hence, multihop communication among nano nodes is currently regarded as the viable solution for nano-network realization. However, designing efficient routing protocols stands as a serious challenge for nano-network practical implementation due to nano-node energy harvesting, processing power, and storage limitations. Simplicity, low energy consumption, and adaptability to highly dynamic network topology are major requirements for successful routing protocol schemes in nano-networks. While precise and efficient routing schemes are a vital element of nano-networks deployment, the current literature falls short in addressing data dissemination in nano-networks to provide efficient and complete solutions. Several researchers investigated well-known routing protocols designed for classical wireless sensor networks for low power and constraint processing classical wireless sensor-nodes [2], [3]. Tairin and colleagues [4] investigate these protocols for the applicability in nano-networks. The authors concluded that these protocols (AODV, DSDV, and DSR) are not directly deployable in nano-networks. Hence, authors propose adapting the AODV by considering a hierarchical version of AODV that involves nano-routers in the packet forwarding only.

Other proposals in literature focused on designing routing protocols specifically for nano-networks. Researchers focus mainly on three types of protocols; flooding protocols, proximity routing protocols and energy conservation-aware protocols. Flooding protocols are motivated due to their simplicity, which conforms to the constraint capabilities of the nano-nodes [5]. Flooding schemes may result in broadcast storms, which results in excessive re-transmission, consequently increasing energy consumption. Proximity routing schemes attempt to improve the performance of flooding schemes by controlling the number of neighboring nodes involved in re-transmissions. Examples of these protocols are CORONA [6] and [7]. Proximity routing protocols mandate addressing of nano-nodes as well as localization. Each node should be individually identified and know its location relative to its neighboring nodes. These algorithms may have limited applicability for practical deployment because they assume fixed network topology, which may be an inapplicable assumption for most of the nano-networks due to the high dynamicity of nano-networks. Energy conservation routing protocols [8] and [9] are specifically designed for self-powered nano-networks. The main objective of these protocols is to minimize energy consumption in nano-networks. This category of routing protocols has to attend to the trade-off between complexity and accuracy in designing these protocols. For example, the schemes presented by Mohrehkesh and Weigle [9] proposed Markov decision process energy model for data dissemination taking into account the current status of energy harvested by the communicating nodes. However, due to the complexity of the proposed model, the authors resorted to a lightweight heuristic scheme, which may provide near optimal solution.

In this paper, we evaluate the performance of three routing protocols; controlled flooding, CORONA, and Hierarchical AODV as representative of three routing protocols categories; Simple flooding schemes, proximity routing schemes, and routing protocols adapted from WSN into nano-networks, respectively. The remainder of the paper is organized as follows: Section II details the system model, Section III provides the simulation setup and performance evaluation results and discussion, Section IV concludes the paper.

II. System Model

IEEE P1906.1 [10] standard specifies a framework for nano-network architecture in general. The framework defines five components as the main building blocks required to deploy nanoscale communication network; message carrier, motion, field, perturbation, and specificity. This definition is meant to be applicable for both Electromagnetic (EM) and molecular nano-networks. Thereby, the standard uses the term component in describing the framework intentionally to discourage the classical notion of a protocol stack or layering. However, the framework is dependent upon the services provided by its components. Thus, protocols are anticipated to facilitate these services defined by the framework.

An instant of the framework in an active network may include the message carrier component that transports a message [11]. The message addressing is provided by the specificity component to facilitate delivering the message to the right receiver. The perturbation component applies to variations in concentration or motion as needed to form a signal recognized by the receiver or the target. Finally, the motion provides the physical operational force to move the message across the network, while the field provides the directional vector of motion toward the receiver/target.

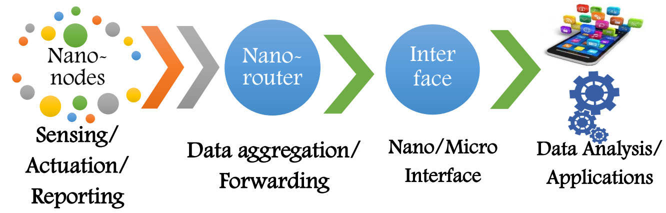

Fig. 1: Nanonetwork System Model

The framework also defines additional elements of a nano-network, such as the nano-network interface to micro/macro classical networks and the relay. The relay provides the ability to increase message concentration or modify motion thereby increasing message delivery rates.

In this paper, we consider a system model aligned with the standardized framework following the definitions in [8] as follows:

- Nano-nodes: These are nano scale devices with constraint energy, memory, computational, and communication capabilities. Nano-devices are deployed into an area of concern for sensing and are capable of performing simplified computation tasks and can transmit data over very short distances.
- Nano-routers: are of higher computational, storage, energy and communication capabilities. They collect and aggregate data from nano-sensors and transmit it to the gateway. They can also propagate simplified basic instruction from the gateway to the nano-sensors.
- Nano-micro/macro interfaces: provide internetworking between the nanonetwork and the traditional networks. They collect and aggregate data from nano-routers and send it to the gateway. They also receive instructions from the micro/macro network to control the nanonetwork. Nano-interfaces communicate using THz communication band as well as classical communication of micro/macro networks.
- Gateway: It interconnects the network to the Internet for remote monitoring and management.

In the system model, the nanonetwork consists of a large number of nano-nodes, fewer number of nano-routers and one gateway. The nanonetwork is deployed in the monitoring area of concern and the nodes can reach the gateway via direct communication or multihop via one router or more as shown in Figure 1.

III. Performance Evaluation

A. Simulation Setup

In this Section, we evaluate the performance of the routing protocols detailed below, which are specifically designed or adapted for implementation in EM nano-network. Nano-Sim simulator built on the NS-3 platform is used for simulation [12]. Table I shows the Simulation setup parameters. The density of the nano-nodes depends on the number of sensor nodes within the coverage area. The coverage area has $1m$

TABLE I: Simulation Setup Parameters

Parameter	Value
Number of Sensor Nodes	$50 - 250$
Number of Routers	$0, 50$
Number of Gateways	1
Volume	$1m \times 1mm \times 1mm$
Tx Range of Nano-nodes	$0.001 - 0.02m$
Tx Range of Nano-routers	$0.02m$
Pulse Energy	$100pJ$
Pulse Duration	$100fs$
Pulse Interarrival Time	$10ps$

x $1mm$ x $1mm$ size. The number of nodes is set to vary from 50 nodes to 250 nodes. The number of routers are set to 50 nodes. Routers are supposed to aggregate traffic from the sensor nodes and forward data to the gateway over a path calculated by the implemented routing protocols in the nano-network.

At the start of the simulation, the nodes are uniformly distributed in the volume of concern. Nodes change their location based on a mobility model detailed below. The rate of successful packet delivery is significantly affected by the number of nodes per unit of volume and the transmission range of nano-sensors and routers. Traffic is generated at a constant bit rate every 0.1 s. The packet size is fixed at 100 bytes. In the following, we present the implemented routing protocols used in this study.

Routing Protocols: We investigate the performance of representative routing schemes designed for data dissemination and forwarding in nano-networks; the nano-sim built-in flooding scheme, CORONA [6], and nano-network hierarchical AODV [4]. Flooding is a basic broadcast scheme, where the node forwards the packet to all of its neighboring nodes. Any node that receives the packet checks if the packet was previously received and if so, the packet is ignored. Otherwise, the node disseminates the received packet to all its neighbors. CORONA is a geographic flooding protocol. Nodes in the nano-networks are assumed to consist of two types; anchor nodes and user nodes. Anchor nodes have higher communication and processing capabilities than user nodes. User nodes are required to localize their position relative to these anchor nodes. The scheme assumes square fixed network topology with four anchors located at the vertices of the square corners. CORONA operates in two phases: setup phase and operation phase. The setup phase is designed to assist user nodes in measuring their distances from the anchors. In the operation phase, a source node selects the anchor nodes and incorporates this information in a packet header proposed by the authors. A receiving node checks its location, the destination location and source location to decide on either forwarding or dropping the packet.

Hierarchical AODV has been adapted to operate in nano-network to simplify the forwarding process of AODV and improve its performance in nano-networks. The RREQ packets forwarding is limited to the intermediate nano-routers to discover the optimal path between the nano-nodes and the gateway. To calculate a path, nano-gateway floods RREQ packets to all the devices within its transmission range. However, RREQ packets are restricted to the nano-routers, thereby any other nano-node receiving the RREQ message will ignore it. Only the nano-routers are thus involved in packet forwarding to establish multi-hop paths. The rationale behind this restriction is the fact that the nano-routers are supposed to have higher energy and transmission capabilities than that of other nano-nodes. Packet dissemination will thereby involve the nano-routers only as intermediate nodes. Consequently, the calculated path might not be the optimal path between the nodes and the gateway.

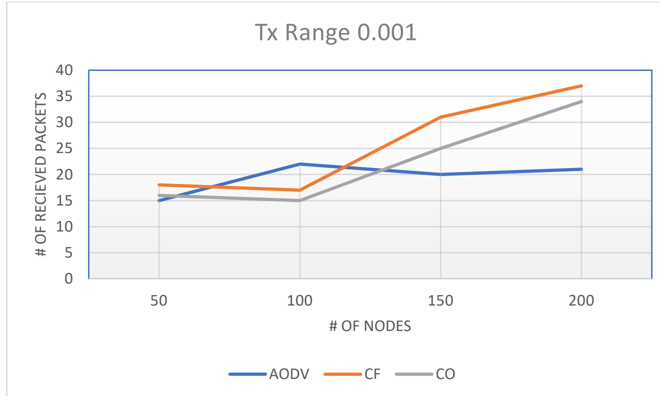

Fig. 2: Number of Received Packets versus Network Density at Transmission Range $1mm$

B. Simulation Results and Discussion

The number of received packets is shown in Figure 2, Figure 3, Figure 4, and Figure 5 as a function of the number of NS nodes (nano-network density). We observed that the number of received packets increases with an increase of network density for all schemes. The low packet delivery performance of all schemes in sparse networks is mainly due to the fact that nano-nodes exhibit a short communication range in the THz band. Hence the probability of disconnected nano-network is larger in a sparse network than that in a dense one. Thus, packets are dropped at nodes whenever a neighboring next hop toward the gateway cannot be found by the routing schemes. The controlled flooding scheme outperform CORONA and AODV for a fixed transmission range. This is due to the fact that each node receives the packet, forward it, as long as it did not see the same packet before. Consequently, the number of nodes participating in forwarding the packet is increased, which increases the probability of packet delivery. CORONA limits the forwarded packets to the anchor neighboring nodes, which are assumed to be three for each node. For AODV, the scheme elects one next hop to forward the packet, and hence, reduces the probability of delivering the packet even more than CORONA.

Figure 2, Figure 3, Figure 4, and Figure 5 show the number of received packets for different transmission range.

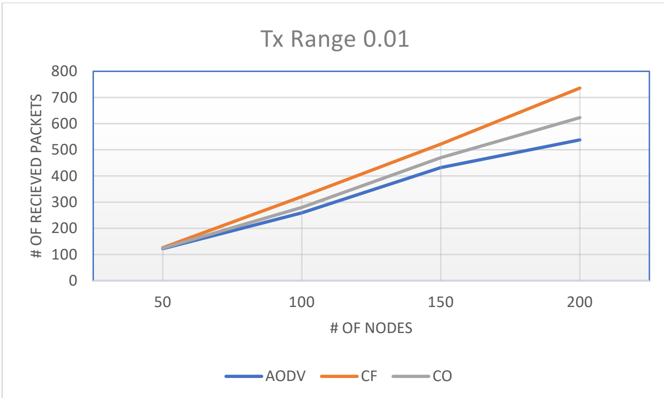

Fig. 3: Number of Received Packets versus Network Density at Transmission Range $10mm$

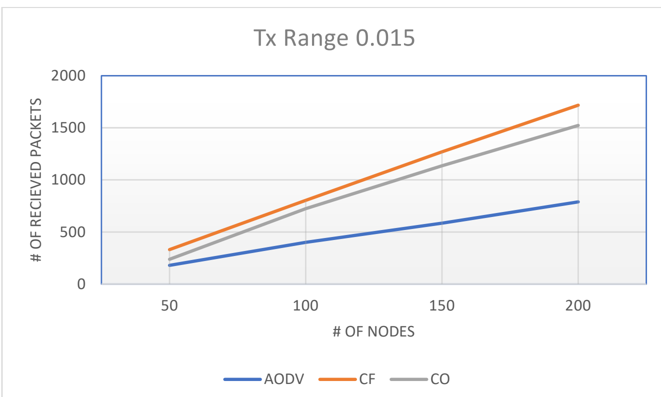

Fig. 4: Number of Received Packets versus Network Density at Transmission Range $15mm$

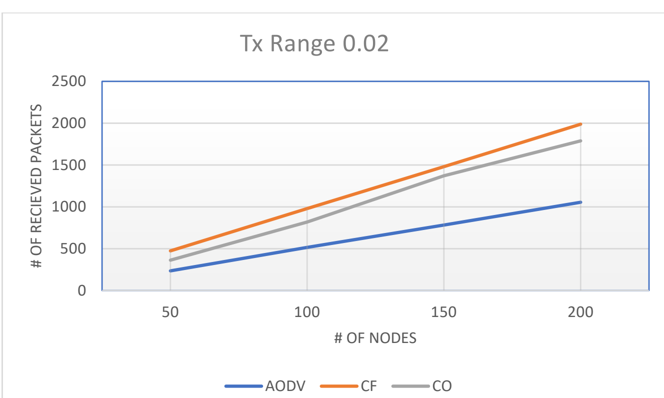

Fig. 5: Number of Received Packets versus Network Density at Transmission Range $20mm$

The Figures show that as the transmission range increases, the number of packets received will increase for a fixed number of NS nodes. The received number of packets are considerably large for a transmission range of 20 mm. Conversely, the number of received packets at transmission range of 1 mm is very low due to a disconnected nano-network at short range. The effect of the longer transmission range is similar to that of the nodes density. It is expected that by increasing the transmission range the probability of connected nano-network increases. The number of hops required to reach the gateway is also expected to be higher for all schemes. However, increasing the transmission range in the case of controlled flooding and CORONA will result in involving more nodes in the forwarding process, which may result in excessive broadcasts.

In general, we can remark that the routing protocols under consideration cannot satisfy the requirements of data dissemination in the nano-network; one solution fits all is not permissible. Flooding-based routing schemes may be more appropriate for sparse networks at acceptable transmission range, while AODV may be applicable for dense network especially since energy consumption is the main concern in nano-networks. A clear conclusion from our study is that carefully designed routing protocols with multi-objective function stand an imminent need for practical deployment in nano-networks. Enhancement of the nano-sim simulator to provide the more realistic simulation of nano-networks is required. Limiting the functionality of the PHY in a simulator to the transmission range does not capture the special characteristics of the nano-network physical layer and the THz communication band. Also, the in-body physical environment is different from on-body or free air environment. Hence, it is necessary to provide researchers with the option to realistically evaluate their proposed schemes using enhanced nano-sim simulator. Another void of the simulator is the simplified implementation of the smart MAC protocol, which is limited to neighboring nodes discovery. Implementing MAC protocols with synchronization and error control schemes can assist in better differentiating the performance of routing and upper layer protocols.

IV. Conclusions

Routing protocols are a crucial part of nano-network design and deployment. Short-range communication in a THz band along with the safety requirement of low energy transmission, especially in in-body applications mandates the use of multi-hop forwarding in nano-networks. In this paper, we studied three routing protocols categories; The flooding protocol, represented by controlled flooding, the geographical based protocols, represented by CORONA, and optimum next hop protocols, resembled by hierarchical AODV. We investigated the performance of the protocols against increasing number of nano-nodes (dense network compared to sparse) and their transmission range. We focused on the number of successfully delivered packets as performance metric. The performance evaluation results show that increasing number of nodes and their transmission range results in increasing the number of