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Alleviating the Routing Issues of Internet of Nano Things by a Simple, Lightweight and Generic (SLG) Routing Protocol

Syed Rameem Zahra[1] and Mohammad Ahsan Chishti[2]

[1,2]*Department of CSE, National Institute of Technology Srinagar, India.*

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Abstract: Scientists have stomped on the idea of dreaming big by thinking small and developing Nanoscience, popularly called Nanotechnology (NT). NT can combine hands with other famous paradigm called the Internet of Things (IoT) and become the next big thing, revolutionizing the world. This paper analyses the applications of NT in various fields and examines its intersection with IoT. It further reveals why it is time that the focus of researchers should shift towards the Internet of Nano Things (IoNT) and unfolds the challenges associated with the complete realization of IoNT. In this paper, we focus on the routing challenge of IoNT networks and propose a lightweight and generic routing protocol for them. Designing a routing protocol for IoNT networks where the sensors display energy, processing capability and communication range constraints is a much essential and challenging task. The protocol proposed in this paper called "Simple, Lightweight and Generic (SLG)" caters for energy-efficient, high throughput, high reliability, and less delay applications of IoNT. We consider the energy value of each node at every stage of the routing process to ensure that they do not lose all of their energy in this process. The protocol also ensures that the highest priority packets reach their destination following a minimum delay. The critical, mathematical and the experimental analysis of SLG confirm its effectiveness in the IoNT environment.

Keywords: Nanotechnology (NT), Internet of Things (IoT), Internet of Nano Things (IoNT), Energy efficient, Lightweight, Generic, Routing.

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1. INTRODUCTION

Nanotechnology has two distinctive, however, imperative implications. One incorporates any technology managing to design something under the size of 100 nanometers while as other points to the actual meaning and alludes to structuring machines in which every single atom and every chemical bond is indicated precisely [1].

NT is studied under two broad headings: Structural NT (top-down approach) and Molecular NT (bottom-up approach), depicted in figure 1. In the former type of NT, the bigger structures are decreased in size to the nano-scale while keeping up their unique properties without atomic dimension control (e.g., scaling down in the size of electronic hardware). Breakthrough in this field may eventually lead to speedy computers, more powerful engines, progressively better medicines and stronger materials. Molecular NT (bottom-up approach) on the other hand is aimed to develop tiniest of the tiny machines like robots, computers, engines etc. atom by atom through the process of assembly or self-assembly [2]. This type of NT is the one that has raised the expectations of free manufacturing and horrors of environmental obliteration [3].

The recent breakthroughs in these two categories of NT have paved the way to the appearance of revolutionary nanodevices that can create, collect, compute, process, and transfer data in the nanoscale dimension [4], thereby endorsing the nanoscale applications among territories like industry, environment, military, medical, manufacturing, etc. [5]. The type of links and the connectivity used between these devices to function have prompted the possibility of nanonetworks chased by the proposition of IoNT. The IoNT uses local gateways to connect nanonetworks to the internet.

IoNT offers advanced solutions to tackle situations that cannot be handled by the former IoT paradigm. For example, it can provide the high resolution of crime scenes and distant objects; it can allow installation of nanosensors inside the human bodies which can provide valuable objective data, etc. However, despite the vast application domain of IoNT, it suffers from several issues relating to addressing, routing, security, etc. which cloud its actual realization.

E-mail: rameemzahra@gmail.com, ahsan@nitsri.net

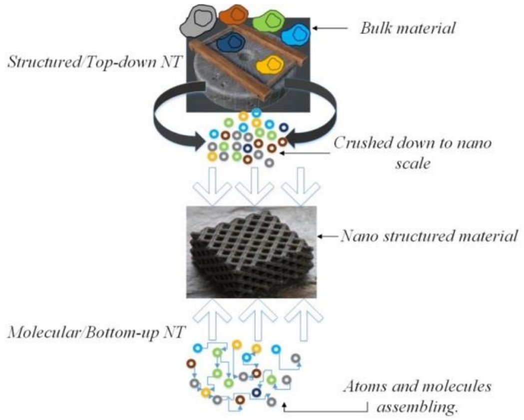

Figure 1. Top-down and Bottom-up Approaches in NT [2]

The inherent features of nanodevices used in IoNT include less processing ability, resource-wise constrained, short communication range in the THz band, and limited energy capability [5]. The nanonetworks deplete energy in almost every step of the way, starting from data sensing and data transmission to data processing. To thoroughly implement the IoNT, various design aspects that arise from these features need to be taken into account in its routing protocols. The researchers are currently trying to develop solutions for different energy-related challenges of the IoNT routing protocols, but no fully developed countermeasures have come out yet [5]. For example, the attempts like [6, 7] have been made to accomplish energy efficiency, but they quickly become impractical in dynamic topologies like IoNT as they assume the static network topologies.

Given these factors, the design and execution of routing algorithms for the IoNT networks are considered as the cardinal and challenging tasks. In this paper, we discuss various technical challenges of IoNT networks, which hinder its true realization. Special attention is given to the routing challenge for which we propose an algorithm called the Simple, Lightweight and Generic (SLG) Routing Protocol. SLG puts minimum pressure on the energy-constrained IoNT nodes, and conveys packets of the message in order on the high bit rate THz band. And thus, SLG takes care of the energy-efficient, high throughput, high reliability and less delay applications of IoNT.

The contribution and construction of this paper are as follows. To highlight the wide span of NT applications, section 2 describes some of the critical areas in which NT can have a tremendous impact. Section 3 reflects the level of research that is being conducted in the field of NT, which sub-fields have acquired more attention over the years and which countries lead this research. Section 4 explains how the tools provided by NT help IoT to widen its span of applications which are otherwise not covered by its micro-level counterparts. It also describes the fundamental architecture of IoNT and the technical issues that curb its potential. In section 5, we have critically analysed the routing protocols used in WSN, and IoNT networks as well as have identified the limitations which make them less efficient and consequently inapplicable in IoNT scenarios. The SLG protocol is discussed at length in section 6. This section explains the requirements of a routing protocol that is meant for the IoNT networks, and thoroughly analyses each phase of the proposed SLG protocol. Section 7 has been dedicated to the mathematical analysis of SLG protocol in various parameters. This ensures that the proposed protocol is energy-efficient, has high throughput and enhances the lifetime of the IoNT network. The experimental evaluation of SLG is presented in section 8. Section 9 concludes the paper.

2. IMPACT OF NT ON VARIOUS FIELDS

With remarkably small size and exceptionally concentrated execution of nanodevices, NT has limitless applications in pretty much every field; medical applications, military applications, environmental applications and applications in manufacturing territory.

A. *Impact of NT on Medical domain*

Present medical treatment can persistently be fine-tuned by utilizing the diagnostic data collected by the implanted medical nanodevices [8]. Examples include pill-sized cameras to see the digestive tract, embedded bone growth and glucose level monitors to assist in the treatment of joint issues and diabetes, respectively. NT can enhance the capabilities of these implanted devices and thereby revolutionize healthcare. A considerate number of nanodevices that are small enough to reach and communicate with individual body cells could be sent into the blood vessels and thus be used to wipe-out the traditional catheter technology [8]. Current research focuses on developing nanoparticles that can target particular cell types for diagnostic imaging and targeted drug delivery. Multiple fixed or mobile bloodborne nanorobots can work in co-ordination for performing tasks like nerve repair, talking with other nanorobots installed in different tissues via short-range communication to share their on-board diagnostic data, thereby acting as library functions for bloodborne robot systems and greatly regulated inflammation responses.

B. *Impact of NT on Defense*

NT has the potential to upgrade this application in spectacular manners. There are plenty of defence-related applications of NT starting from sensing weapons of mass destruction (WMD) to smart armours and active camouflage, from medical aids to self-healing nanoelectronics. NT is quickly rising as another frontier in biodefence, for it is being utilized in the development of biosensors, e.g. an NT based nerve-gas agent detecting sensor has been developed [9]. Moreover, NT is believed to play a pivotal role in the creation of next-generation unmanned aerial/unmanned combat aerial vehicles. NT also offers solutions to the threats from WMD terrorism. It provides protection against the chemical agents like GD, GB, HD and VX by having nano-particles like CaO, AL_2O_3 and MgO that combine with such chemical agents and quickly decompose them, faster than any other solution. NT would accelerate the building of less weight barrel-type weapons. The reduced weight brazenly implies increased speed, higher range and a slash in the size of the carrier.

C. Impact of NT on Environment

NT has great promises in all the crucial sectors of the environment: soil, water and air. The exciting field of NT has made significant achievements in the remediation of chlorine and heavy metal (Mercury, Cadmium, Lead) contaminated soil with the use of zero-valent iron nanoparticles. The overconsumption and the unfortunate contamination of freshwater sources have forced the scientists to consider seawater as an option for drinking water. But, seawater has excessive amounts of salt content, that make it unfit for human consumption. Desalination is the only but expensive alternative for transforming it into a human consumable form. Carbon nano-tube layers can possibly lessen desalination costs. Likewise, nano-filters could be utilized to remediate ground/surface water polluted with dangerous materials. Lastly, waterborne contaminants could be detected with nanosensors [10]. Contamination of air is another potential territory where NT can offer an extraordinary guarantee. Indoor air volume could be filtered using nano filters or carbon nanotubes. Nano-filters could be connected to mobile tailpipes and industry smokestacks to filter out pollutants before they enter the environment. Also, toxic gas leaks could be caught at an early stage by using nano-sensors.

D. Impact of NT on the manufacturing industry

There are two attributes of having the capacity to control objects at the atomic level that ultimately loan a distinctive advantage from the manufacturing point of view and empowers a set of production techniques largely alluded to as nanomanufacturing [11]. First, by using materials at the nano-scale level, one can expand the surface area for the same mass of material used, which could be genuinely significant for many manufacturing activities. Secondly, quantum effects arise at the nano-scale level. These effects could affect the optical, electrical and magnetic properties of manufacturing materials, exploiting which could lead to the creation of materials with tailored strength, lightness, conductivity, less/no overheating, etc. These materials can be nano-scale in one (thin films, layers and surfaces), two (nanowires and nanotubes) or three dimensions (nano-particles). NT based fabrication techniques and nano-scale materials would be useful for six manufacturing industries, as shown in figure 2.

Considering the disruptive and enabling technology characteristics and these applications of NT, it is concluded that NT has tremendous potential to achieve things that were almost inconceivable with the old technologies. The core strength of NT is not only that it provides better products but also an immeasurably enhanced manufacturing process. This is the reason that it is relied upon to bring the next Industrial Revolution [12].

Figure 2. Manufacturing Industries Benefiting from NT [12]

3. RESEARCH TRENDS

To visualize the level of research that is conducted in the field of NT, we have analyzed the number of patents that were granted and published by the most important patent offices of the world, i.e., United States Patent and Trademark Office (USPTO) and the European Patents Office (EPO) during the year 2016 and 2017 [13,14]. Figures 3 and 4 show the top 10 countries of the world from the perspective of granted and published patents in USPTO, while as figures 5 and 6 confirm the top 10 countries of the world from the outlook of granted and published patents in EPO.

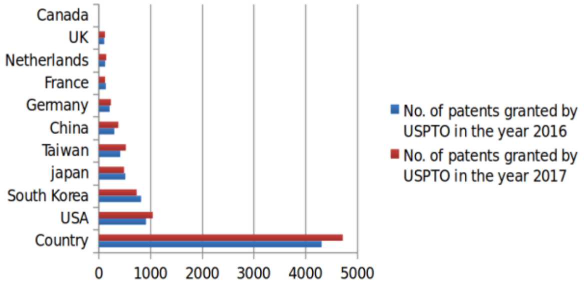

Figure 3. Top Ten countries in the number of NT Granted Patents Published in USPTO in 2016, 2017

The figures 3 and 4 demonstrate that a total of 19,563 NT related patents were published in USPTO in the year 2016 out of which 8,484 are granted patents. A total of 20,187 patents were published by USPTO in the year 2017 out of which 9,145 are granted ones.

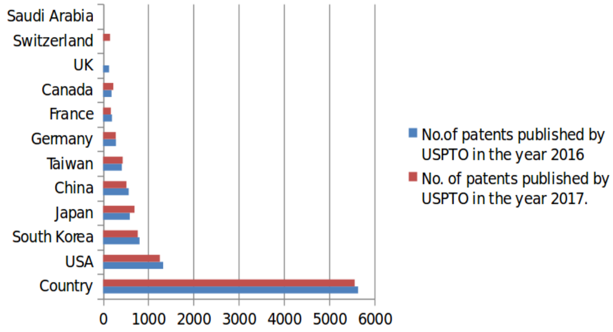

Figure 4. Top Ten Countries in the number of NT Patents Published in USPTO in 2016, 2017

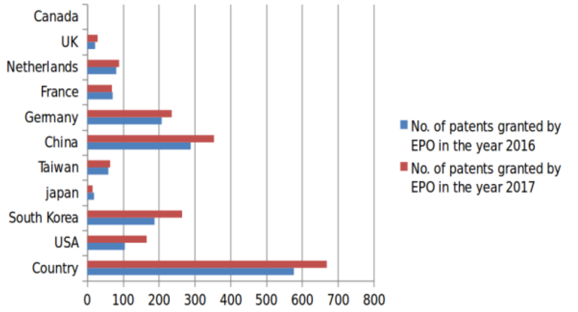

Figure 5. Top Ten Countries in the number of NT Granted Patents in EPO in 2016, 2017

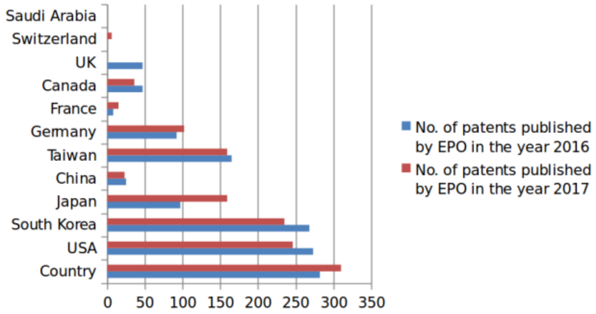

Figure 6. Top Ten Countries in the number of NT Patents Published in EPO in 2016, 2017

Similarly, the figures 5 and 6 indicate that a sum total of 3,589 NT patents were published in EPO in the year 2016, out of which 2006 are granted. 4,019 were published in the year 2017 in EPO among which 2,386 are granted.

Although, these statistics point to the fact that the linkage of NT with industry is proliferating, the trend in figure 7 shows that not all the sub-fields of NT are growing at the same pace [15]. These numbers orchestrate the fact that the manufacturing of nanosensors is a complex task and a field that is still in its infancy and has a lot of issues to tackle.

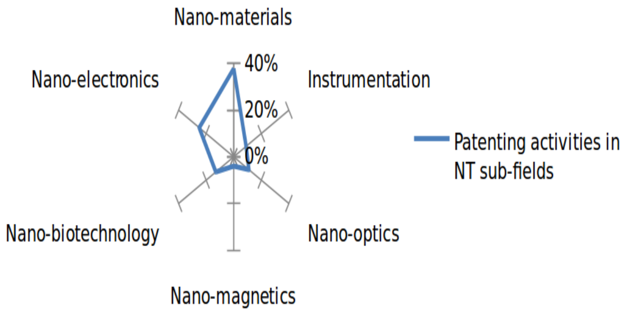

Figure 7. Patenting Activities in NT Sub-fields [15]

4. LUNGING TOWARDS THE INTERNET OF NANO THINGS (IONT)

IoT is a novel paradigm that interfaces the inescapable nearness around us of an assortment of things to the internet by utilizing wireless/wired communication technologies to achieve wanted objectives. Since the idea of the IoT was presented, we saw its emergence in diverse fields starting from domotics, e-health, real-time monitoring of industrial processes, and intelligent transportation of people and goods, amongst others, made tangible by installing all forms of devices with sensors, actuators and communication abilities best suited to the application they support [16]. IoT allows everything starting from a pencil to a mighty truck to stay connected. This transformation from dull and disconnected lives of people into smart and connected ones, however, requires every individual to be surrounded by a massive number of visible range sensors (equal to the number of objects s/he connects with) that will communicate the acquired information [17], through the internet to the ultimate user. Therefore, if a person is surrounded by just 100 everyday objects, portability will become a huge issue.

The foundation of IoT is laid on two technologies: Radio Frequency Identification (RFID) and Wireless Sensor Networks (WSN). While RFIDs have the advantage of small size and battery-less operation, they can be installed in almost any device, but they lack the storage, sensing and processing abilities. WSNs, on the other hand, offer IoT with these abilities; however, the complexity, resource constraints of existing sensors and their size restrict the effectiveness of this approach. Hence, novel communication technology for IoT is the need of the hour.

NT is providing the engineering community with a new set of tools enabling the development of a new generation of devices like nano-batteries [18,19], nanotransistors for future nanoprocessors [20,21], and nanosensors [22,23] which do better than their microscale counterparts [24]. Moreover, the terahertz band (0.1–10 THz) opens the door to ultra-broadband communications amongst nanodevices [25, 26]. Nanomaterials are also expected to be used in the development of tiniest photodetectors [27] and acoustic transducers [28], which could be used to transmit multimedia content at the nano level. These nano-cameras and nano-telephones will have the capacity to catch visual and acoustic data with a phenomenal resolution, accuracy and precision, a lot higher than current microscale cameras and microphones.

The amalgam of ubiquitously installed nanodevices and available communication network plus the internet describes a new paradigm of a cyber-physical system called the “Internet of Nano Things” (IoNT). If the nano multimedia sensors are used, it is called the “Internet of Multimedia Nano Things” (IoMNT). The IoNT isn't just consistent with the imagined applications of IoT [29]; however, it additionally empowers further developed applications in assorted fields.

A. Applications of IoNT

IoNT solves the portability issue by using the nanosensors in place of usual-sized sensors. Although this benefit is enough for shifting the focus from IoT to IoNT/IoMNT, there are situations where the former would not work at all. Some of them are listed below:

1) *Biomedical Applications:* Better health monitoring and treatment frameworks which consolidate chemical and biological nanosensors, nanocameras with extremely high-resolution powers and ultrasonic nano phones for catching diseases like cancer in their initial phases and treatment of various other ailments. Another example is that of parents who wish to keep a check on their child’s addictive drug use. They can do so by installing particular nanosensors inside the body of their child. These sensors will provide valuable objective data regarding the time and contexts of drug use. Nanosensors are better in this situation because visible range sensors deployed outside bodies could be taken off.

2) *Defence and Security Systems:* IoNT with the aid of imperceptible nanocameras and ultrasonic nanophones can collect data from any territory without the knowledge of the enemy [30]. Also, a secure nanonetwork could be created using nanodevices for information exchange. IoNT covers the issues of detection of visible range sensors by enemies as the nano devices are invisible and undetectable. The IoMNT sensors can also detect temperature variation in nuclear or atomic bombs.

3) *Enhanced Multimedia Applications:* IoNT makes it possible to obtain ultra-high resolution images of crime scenes and distant objects. The former can be a great help in the department of forensics while the latter can assist in the far-field satellite or aerial imaging. High definition video conferencing is another application.

The thing to be noted in all of these applications is that the number of sensors required to bring about the precision that they call for is enormous. When the number of sensors used for obtaining any information increase, it increases the amount of data for reliable transmission.

B. The Architecture of IoNT Network

The nano elements which sense, analyze or store any information as well as interact with each other for providing the user with the desired information together constitute the architecture underlying the vision of IoNT. This architecture is diagrammatically shown in figure 8, while its constituent elements are described below [24]:

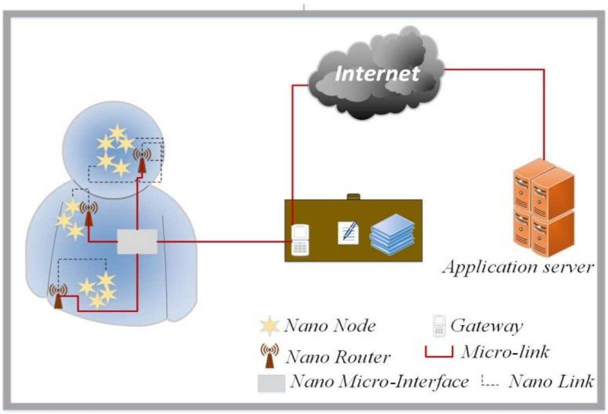

Figure 8. The Architecture of IONT [24]

1) *Nano node:* These refer to the smallest of all the nanomachines that can do just the basic calculations. They are constrained because of their puny sizes in their memory, communication capability, energy, and transmission power. Example of such machines includes human body nanosensors.

2) *Nano router:* They are responsible for collecting and forwarding the data coming from a group of nanodevices. These nanomachines have better compute abilities, larger memories, greater energies and transmission powers than nano nodes/devices. By using some trivial control commands like switch on, switch off and sleep nano routers control nano nodes to some level.

3) *Nano-micro interface:* To connect the nanoworld with its micro counterpart, the nano-micro interface comes into play which collects the data from multiple nano routers and transmits it to the microscale. It also communicates the information coming from the microscale to the nanoscale devices.

4) *Gateway:* This device is responsible for transferring the joint authoritative control of the system under observation to the internet, i.e., it forms the interface between the internal nano network and the external internet.

C. Technical Issues in IoNT

Albeit various advantages, the actual realization of IoNT is fogged up by several issues that require addressing like extreme heterogeneity of the multimedia nano things in their architecture and capabilities. The diverse communication requirements typical for each scenario are another severe research challenge. Table I describes significant research challenges that need to be overcome for achieving the actual realization of this novel networking paradigm.

TABLE I. TECHNICAL CHALLENGES IN IONT

Challenge	Description	Future Directions
Multimedia data compression and signal processing [31]	The spectral response and pixel density of multimedia nanodevices are very high, implying the amount of data that these devices will have would be huge (several terabits/sec). Architecture and the ways of communication in IoNT are entirely different from those of IoT and WSN; their data compression techniques cannot be taken up. Quicker nanoarchitecture and high-density nano memories are needed.	New and efficient compression techniques should be developed for nanocameras and nanophones for making them energy efficient and removing redundancy. Develop new architectures for nanocameras and nanophones that send computation and other complexities towards pixel elements. Propose faster communication techniques among nanodevices.
Modulation and encoding [32]	The THz band employed in IoNT communications offer a far greater transmission bandwidth than the traditional wireless systems. The schemes of modulation and encoding which exist were primarily designed for the channels of limited bandwidth.	The schemes meant for both need to be revamped as the existing ones are intended only for WSN communications-not using the THz band.
Terahertz band channel modelling [33]	Terahertz band represents the least explored bands of the EM Spectrum. The available channel models for lower frequency bands cannot be used for this band, since they lack the ability to capture effects like attenuation and noise, particle scattering or scintillation of terahertz radiation.	Analyze the impact of terahertz radiation on living beings. Examine how the transmission window's achievable data rates and capacities are affected by multi-path propagation in IoNT.
Localization techniques	The traditional node localization techniques like Global Positioning System (GPS) etc. are highly erroneous and cause extra consumption of energy.	Novel techniques of node localization are needed in IoNT networks, and thus it marks yet another area of open research.
Addressing [34]	IoNT employs a plethora of devices, each of which will require an address. Lengthy addresses will be needed if traditional addressing schemes are employed.	Develop new addressing schemes that can support the hierarchy of IoNT network or use IPv6.
Security [35,36]	Nanodevices are exposed to all kinds of assaults as they remain unattended and are almost invisible. Unattended nature welcomes intentional physical attacks while as invisibility calls for involuntary physical damage. Existing security procedures cannot be used on IoNT for they do not address the uniqueness of the terahertz band.	Create novel authentication and data integrity techniques for IoNT. Create ways for ensuring user security and privacy in IoNT.
Routing [37]	Usage of the THz band brings challenges in IoNT routing as well. Existing neighbor discovery (ND) and other routing protocols cannot be used for: The THz band offers an exceptionally high bit rate. The existing routing protocols do not understand such physical layer properties. The architecture of IoNT demands nanodevices to interact with one another.	Device a new ND protocol that will take into consideration the highly directional nature of nano-antennas. If this is made possible, the real-time location of 2 neighbors can be evaluated. Develop a routing protocol that first uses the ND protocol and then calculates the probable wait time to the next nanomachine.

5. IONT ROUTING PROTOCOLS RELATED WORK

The unique characteristics of IoNT networks need to be taken into account while designing its routing protocol. These characteristics include the use of short-range, high bit rate THz band for communication, restricted energy, and low processing abilities of sensory units.

Researchers continue to investigate different routing challenges in terms of energy, but till now, no solid solutions have been proposed [38]. Most of these solutions stem from Wireless Sensor Network (WSN) based schemes [38-41]. However, these schemes require static network topologies that render them infeasible and impractical in IoNT scenarios where the nodes are continuously moving, thereby, creating random topologies.

Table II discusses some of the traditional WSN protocols and explains what prevents their direct implementation in IoNT networks.

TABLE II. WSN ROUTING PROTOCOLS INTENDED FOR USE IN IONT

WSN protocol	Protocol highlights	Critical analysis	Conclusion
Sequential Assignment Routing (SAR) [42]	Multipath routing protocol, therefore, has high packet reachability. First-ever routing protocol to consider Quality of Service (QOS) issues from energy conservation and packet priority point of views.	The mechanism employed for creating multi-paths causes exhaustion of nodes vital energy.	Insufficient for energy-constrained IoNT networks.
Reliable Information Forwarding using Multipaths (ReInForM) [43]	Multipath protocol. Delivers packets at desired reliability levels, incurring fair communication costs.	It doesn't take into account the useful lifetime of the packet while picking paths. This leads to multiple transmissions, which lead to extra consumption of energy and wastage of valuable channel bandwidth.	Not suitable for constrained IoNT network.
Geographic Adaptive Fidelity (GAF) [44]	GAF balances the number of nodes used for forwarding the packets.	GAF makes it essential to accurately locate the sensors, which is a massive challenge in mobile IoNT networks.	Since the design of novel localization algorithms for IoNT networks is still an open area of research, GAF is Impractical for mobile IoNT's.
Geographic and Energy Aware Routing (GEAR) [45]	Only forwards queries to specific regions. Hence, it tries to be energy efficient by omitting unnecessary communication costs.	Nodes need to be localized. Hence, specific hardware units like GPS are required. GPS units are usually erroneous and cause heavy energy wastage.	IoNT network cannot utilize the localization scheme as used in GEAR and hence it is unsuitable.
Nearest Neighbor Algorithm (NNA) [46]	The idea of NNA is to utilize the shortest path in every communication, i.e., even between 2 nodes. This procedure will eventually lead to the creation of the shortest path between the source and destination.	4-direction transmission is used, which indicates that instead of the shortest path, NNA considers the shortest neighbor, which results in an unnecessary increase of hop counts and therefore extra energy consumption.	Unfit for IoNT networks for being energy-intensive.

Nonetheless, researchers have tried to make modifications to these protocols and also suggested new ones to incorporate the specific requirements of IoNT routing protocols in their works. However, the proposed schemes suffer from limitations, which make them less efficient and sometimes inapplicable in IoNT scenarios. Table III lists some of the nano-network specific routing protocols and highlights their downsides.

TABLE III. SPECIFIC NANO-NETWORK ROUTING PROTOCOLS AND THEIR ISSUES

IoNT routing protocol	Protocol highlights	Critical analysis	Conclusion
Tsioliaridou. A et al. [6]	Addresses all the nodes of the network. Is a geographic routing protocol. 2 types of nodes are considered, one of which has higher processing and communication abilities.	Static topology is assumed. Addressing each node in IoNT is a challenge.	Addressing is a major issue in IoNT's. Moreover, static topologies are considered making it inapplicable in IoNT.
Massimiliano. P et al. [41]	Uses hierarchical cluster-based architecture for developing this energy-efficient protocol. Data forwarding can either be direct or multi-hop depending upon the energy that the process will consume.	The procedure employed is complicated and requires extra computations, which become a hindrance for computationally handicapped nanodevices.	The protocol is computationally-intensive and therefore, less efficient in IoNT.
Liaskos.C et al. [7]	Based on their quality of reception, it classifies nodes into 2 types: infrastructure and single-user nodes. Only infrastructure nodes are permitted to	In spite of the fact that this protocol streamlines the communication model, it disregards the complexity and cost of this classification as well as the real-time processing of each packet.	Not sufficient for IoNT.

	forward packets to their neighbors. The classification is dynamic and adaptable.	Moreover, it also expects the topology to be static, which is not the situation in IoNT.	

In this paper, we propose a Simple, Lightweight and Generic (SLG) algorithm as a routing protocol which will take care of the limitations in already existing routing protocols for realizing the IoNT concept. It is explained in detail in the next section.

6. SIMPLE, LIGHTWEIGHT AND GENERIC (SLG) ROUTING PROTOCOL FOR IONT

To actualize the idea of IoNT and IoMNT, we need to utilize various nanodevices that will sense the data from multiple sources and help it to reach the ultimate destination. This entire consortium of nanodevices is represented to the outside world by a gateway device. The nanodevices additionally require an exchange of data among themselves to create right, explicit, and productive information concerning the particular thing they sense.

Accordingly, the principal challenge in IoNT/IoMNT routing is the way the packets are routed between various nanodevices/machines as they are incredibly small and exceptionally restricted resource-wise. This section discusses in detail the requirements of a routing protocol that has to be designed for an IoNT network and the SLG algorithm.

A. IoNT/IoMNT routing protocol requirements

To realize the IoNT paradigm, a routing protocol must satisfy the flowing requirements:

- Since the nano nodes are energy inhibited, to save their energy for the functions they intend to do, every stage of the routing protocol must consume minimal energy, i.e., it must be lightweight.
- It should not be computationally intensive, i.e., it should be simple.
- It ought to likewise be particularly basic for reducing the hardware complexity, and the pressure of routing on tiny and constrained devices.
- As THz band is utilized for communication, the routing protocol must be able to deal with extremely high bit rates or in other words; it must have high throughput.
- As the devices display vast heterogeneity, the protocol must be generic.
- Finally, the routing protocol must be able to convey the packets of the message in the desired order incorporating the least delay.

Keeping in view each one of these contemplations, we propose a Simple, Lightweight and Generic (SLG) routing protocol for executing IoNT/IoMNT routing.

B. Assumptions

For the implementation of the proposed routing protocol, we have made the following assumptions:

- We expect absolutely zero immediate correspondence among the nano machines, i.e., only single-hop or multi-hop communication is allowed.
- Nanodevices interact through a nanorouter located in the vicinity.
- Routers are assumed to have static and stable positions.
- Each nanodevice is specified with an identifier.
- Energy devoured for sending and receiving of information is same for all the nanodevices.
- The communication channel is expected to have a constant signal to noise ratio (SNR).

C. Algorithm

SLG is a novel proactive routing protocol that does not require the whole course from a nanodevice to the corresponding nanorouter to be known in advance. By sparing the nano nodes from remembering the entire route, vital energy of these originally energy-constrained devices is saved. Each nanodevice is made to store only the information of its neighbors because of which its memory requirements are kept under check. As such, each node's neighbor table contains only two fields: "Time-count" required in reaching the nanorouter through a "Next-hop" neighbor and the remaining energy of the nanosensor device.

This group of nanonodes is assumed to occupy a two-dimensional area as per a spatial homogenous Poisson process, the rate of which is equivalent to the density 'D' of nano devices, i.e., the number of nanodevices per unit of area. As per this, the probability of having 'n' nanodevices within the reach or the neighborhood of a particular nano router lying in an area 'A' is given by equation 1 as [41]:

$$\frac{[DA]^{n} e^{-DA}}{n!} = P(\text{‘}n\text{’}nanodevices \in area\text{‘}A\text{’}) \qquad (1)$$

SLG is a generic routing protocol as it is designed in such a manner that it is independent of any architectural design constraints. The essence of SLG is marked by its simplicity, less overhead for routing, less energy consumption minimum delay, and high throughput, a combination that represents all the essential pre-requisites to create an effective routing procedure for executing an IoNT/IoMNT network. SLG runs in 3 phases: Initialization phase, packet forwarding and route maintenance. Each one of these phases is explained below.

1) *Initialization phase:* This stage is initiated by the routers that are connected to various nanodevices and its objective is to fill in the neighbor tables for each sensor device. Amid the procedure, nanodevices are allowed to broadcast just one time for decreasing the overhead for routing. Once this stage completes, all nanosensor nodes are set to send any packets to the nanorouter device. Route maintenance is employed for updating any changes to the neighbor tables.

    a) *Execution of Initialization phase:* The nanorouter broadcasts an initialization routing control packet to all the sensor devices in its range, which contains the ID of nanorouter node, start-time, end-time and residual energy value, etc. The start-time is the nano router's clock time when it transmitted routing control packet, and the end-time is the estimated time up to which the packet is valid in the network. The sensor node on receiving routing control packet checks the end-time and sets/updates its neighbor table and forwards it to other sensor nodes in its vicinity. When the sensor node receives a routing control packet from other nodes, it first checks for the validity of the received packet by comparing its clock time with the end-time field of the received packet. If the received routing control packet is valid, then the receiving node creates a new entry for the neighboring node (if not already present) or updates the entry (if it already exists in the neighbor table), appends its residual energy value to routing control packet, and forwards it to other nano nodes in its vicinity. If the received routing control packet is invalid, then it discards it and does not forward it. The whole process of constructing the neighbor table at a particular nanosensor device during the initialization phase is depicted in algorithm-1.

Algorithm – 1: To create neighbour table at each nano sensor device during initialization phase

```
For-each $P_{RC}$ received by nano node "i":
  elapsed_time = $T_i - t_s$
  if($T_i > t_e$), then:
    discard $P_{RC}$
  else:
    if($S_N$ in $NT_i$ and elapsed_time<TC($S_N$)), then:
      set TC($S_N$) = elapsed_time
      set E($S_N$) = received-energy-value-of-$S_N$
      Append RE(i) to $P_{RC}$ and forward $P_{RC}$ to other nano nodes in range
    end-if
    if( $S_N$ not-in $NT_i$):
      create new entry for $S_N$ in $NT_i$
      set next-hop field = $S_N$
      set TC($S_N$) = elapsed_time
      set E($S_N$) = received-energy-value-of-$S_N$
      Append RE(i) to $P_{RC}$ and forward to other nano nodes in range
    end-if
  end-if
end-for
```

Symbols used in Algorithm 1:
SN – Neighbouring nanosensor node.
NTi – Neighbour table of nano node "i."
ts – Start time.
te – End time .
TC(x) – Time-count field in NTi for nano node "x."
E(x) – Energy field in NTi for nano node "x."
Ti – System clock time of node "i."
PRC – Routing control packet.
RE(i) – Residual energy of "i."

In this manner towards the end of the initialization phase, each one of the sensor devices can route their packets proficiently to the desired destination relying upon the minimal estimation of the time required to reach the nano router. The nanorouters always have a nano-micro interface and a nano gateway in their vicinity with which they are configured to allow them to connect with the micro-world outside. To work at an atomic level, these nanomachines can either make use of molecular communication or electromagnetic Communication. Molecular Communication takes inspiration from the human body, e.g., to contract or relax a muscle in the human body; nerves send a specific type of molecule called Acetylcholine [3]. When a muscle receives a molecule of acetylcholine, it contracts. Similarly, in nanonetworks, particular types of molecules are sent by a transmitter towards a receiver to mean some specific information. This method is preferred when water is the medium. Electromagnetic transmission is used in case the medium of communication is air. Smaller devices imply smaller antennas, which in turn point toward increased frequency needs for message transmission. To allow such communication, Terahertz (THz) band has been reserved for nanonetworks that allow a node to send its message within 10^{-15} seconds, no matter the size.

It is important to note that the mandatory time to reach the router is not hop-count based but absolute time based. This is because learning about the absolute time lessens the delay and decreases the network's congestion. Also, the clock synchronization and distribution is the responsibility of the nanorouter because the initialization routing control packet is broadcasted by the nano router and contains the start-time and end-time. To perform this task, the nanorouter has to monitor the network nodes in its vicinity continuously and synchronize with them, but the nano router has limited energy resource. To fix this problem, since the position of the nanorouter is fixed, we can attach an additional power source to nanorouter, thereby making it to monitor the network nodes continuously and accomplish network synchronization.

b) *Critical Analysis of the initialization phase:* Assume there are two paths for exchanging the data between nanorouter ‘B’ and the nanodevice ‘A’ as shown in figure 9. There are three intermediate nanonodes in the first path and only one intermediate node in the second path. If we pick hop count as a metric as do most of the routing protocols meant for WSN, then the second path is the ideal one, but in the off chance that this path is congested, every packet routed on this path would be dropped which shall increase the delay in the system. To maintain a strategic distance from this situation, SLG utilizes the idea of absolute time. This time is updated at the route maintenance step.

In case route maintenance procedure identifies that the second path is congested, it spontaneously updates the absolute time that will make the routing procedure to proceed through “path 1” thus decreasing the delay and increasing the throughput.

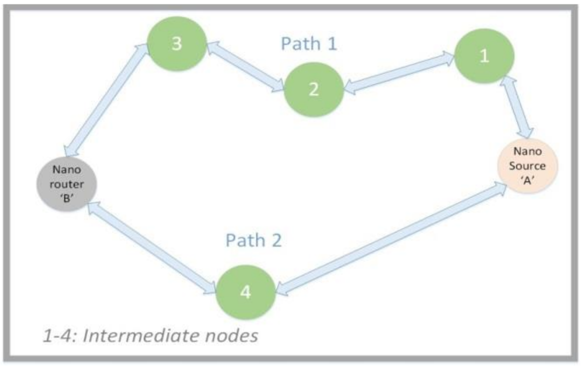

Figure 9. Paths to reach Nano Router from a NanoSource

2) *Packet Forwarding:* Exactly when a nanodevice has an information packet to send, it first assesses the priority of this data packet. In case the packet has an elevated priority (like a data signalling packet), then it chooses the node with minimum time-to-reach the target node from the neighbor table. If a packet, on the other hand, is a low priority regular packet containing a basic message, then it picks that node from the neighbor table that has a lot of energy left for forwarding purposes. The rehashing of this procedure happens at each intermediary node till the time packet reaches the preferred router that then courses it to its final target. The packet header is shown in Table IV.

TABLE IV. PACKET HEADER

p_src	Originator of packet
p_dest	Destination node
p_srcack	Acknowledgement originator
p_seq_num	Sequence number of packet
p_priority	Priority of the packet
p_start_time	Packet start-time at each node
time_to_reach	Time required to reach the Nano router
RE(i)	Residual energy of the node

a) *Critical analysis of packet forwarding phase:* Following SLG protocol, any signalling data will reach the destination as fast as could be expected under the unique IoNT characteristics. Moreover, packets are moved from one node to another in a manner that guarantees the energy of nodes will be devoured consistently and judiciously- increasing the viable lifetime of the network. The overall overhead of route maintenance is subsequently decreased by updating residual energy instantly during this phase. To keep up the equilibrium between the residual energy values of various nano nodes, an ideal assessment regarding the choice of paths/routes for message and signalling packets has to be made.

3) *Route maintenance:* Following SLG protocol, to remove the overhead of route maintenance on nanonodes, only nano routers will be responsible for maintaining the routes. For maintaining the routes, nanorouters will periodically send routing control packets to detect any change in the topology. If it is detected by the nanorouter that the energy of a particular node is very less, it sends it to the sleep mode and stops sending any more control packets. These control packets will be sent periodically only to the nodes belonging to regions displaying heavy and frequent transmissions, because the nodes which are either sleeping or low in energy or not sending packets do not require the routes much.

Also, in the regions where fewer transmissions are happening, nano routers will send the updates to the critical nodes (nodes which are central for multiple paths in a network). Therefore, if at any point, a node wants to send data, it can do so by obtaining the updated routes from the critical node. In case, no critical nodes are available, nanorouters will send updates to the nodes after a fixed number of intervals (a period that is neither too big nor too small for inactive nano nodes). This is to keep the less active nodes updated with the new routes.

Moreover, in SLG, the nanorouters make delays in sending acknowledgements to sources from which they receive any signalling or data packets. This delay should be made up to the point they receive acknowledgements from the ultimate destination. Once the acknowledgements are received, routers can forward them to the actual sources.

a) *Critical analysis of route maintenance phase:* Although, the process of sending control packets will consume energy, it will still be less than the procedure that requires continuous route maintenance by the nodes themselves or the one where the nano router sends control packets to every nano node whether or not they need it.

Also, the procedure of first recognizing the ultimate destination expands the reliability of the network.

7. MATHEMATICAL ANALYSIS OF ENERGY SAVING BY SLG

This section is dedicated to the mathematical analysis of SLG in various parameters, i.e., energy-saving, throughput, and IoNT network lifetime.

The probability of energy-saving during congestion in multi-hop paths by SLG for a particular nanodevice ‘d’ may be defined as the likelihood of achieving the total average energy per bit utilization while using multi-hop communication to reach the nanorouter $E_{m\text{-hop}}$ (d) is less than the average energy per bit utilization while using the single-hop transmission $E_{s\text{-hop}}$ (d). This is represented as:

$$P_{ES}(d) = P_r\{E_{m-hop}(d) \leq E_{s-hop_{congested}}(d)\} \tag{2}$$

Or

$$P_{ES}(d) = 1 - Pr(S - hop_{congested} byd) = Pr(m - hopbyd) \tag{3}$$

Above equations suggest that probability that the energy is saved by the node represented by P_{ES} (d) during the events of congestion in single-hop paths is equal to the probability that SLG chooses the multi-hop path for routing and not the congested single-hop path. The procedure used in SLG guarantees that in case there is congestion in any path, a free path is chosen.

Let the distance of the source node ‘d’ from the intermediate node be denoted by x_d, as shown in figure 10. The total energy consumption by a node to transmit an entire packet in an s-hop path is equal to the sum total of energies consumed by the node in transmitting every single bit of it to the nano router.

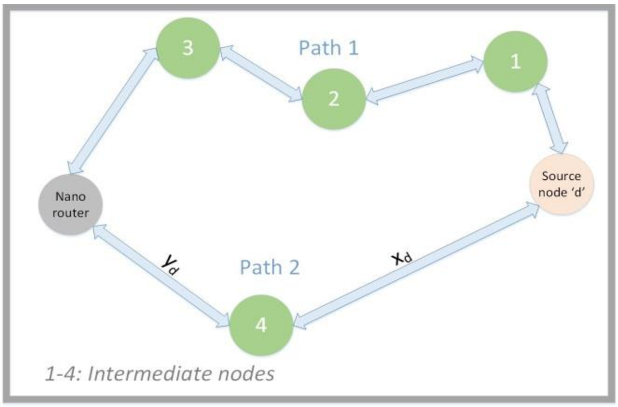

Figure 10. Various Distances in the Path from Nano Source to Nano Router

Let the energy consumed per bit to travel a distance of x_d be denoted by $E_b(x_d)$ to reach the intermediate node from the source nano node. Also, let $E_b(y_d)$ be the energy spent in travelling a distance of y_d for reaching the nano router from the intermediate node. Let E_{rec} be the energy exhausted at the intermediate neighbor node for receiving one bit. This energy is constant and depends on the design. Moreover, when the congestion occurs in a network, a single-hop communication pathway may drop any packets that it receives which shall not only increase the delay but also increase the energy consumption of the node for continuous retransmissions. The source node consumes energy while waiting to receive the acknowledgement of sent packets from the router. Let this energy be denoted by $E_w(d)$. A multi-hop path, on the other hand, will transmit the packets in one transmission and won’t face any $E_w(d)$. Consequently, equation 2 becomes:

$$P_{ES}(d) = \Pr\{ E_{m-hop}(d) \leq E_b(x_d) + E_b(y_d) + E_{rec} + E_w(d) \} \tag{4}$$

Besides, the average energy consumption per bit denoted by $E_b(l)$ is defined by the ratio of two functions that are both directly proportional to the distance that has to be covered- Source node’s transmission power that is absolutely essential for ensuring a constant signal to noise ratio (our assumption) at the receiver positioned at a distance ‘l’, and the maximum bit rate transmission. Therefore, if TP_l represents the transmission power, BR_l denotes the maximum bit rate then,

$$E_b(l) = \frac{TP_l}{BR_l} \tag{5}$$

Above equation indicates that higher the bit rate, lesser the energy consumed to transmit each bit. By using the THz band and the concept of absolute time for route updation, the transmission bit rate of each node increases substantially, which decreases the energy consumed for transmitting every bit.

A. *Mathematical analysis of Throughput by SLG*

The throughput $\alpha(l)$ is described as the maximum bit rate of a node for a distance ‘l’ and is given as:

$$\alpha(l) = BR_l \times \gamma^c(l) \tag{6}$$

Where $\gamma^c(l)$ is the Critical Transmission Ratio (CRT) [42] and is described as the ratio between the rates of energy harvesting $\varepsilon_{har}(l)$ and energy consumption $\varepsilon_{con}(l)$ of a nanosensor during the time it transmits. It is given by:

$$\gamma^c(l) = \frac{\varepsilon_{har}(l)}{\varepsilon_{con}(l)} \tag{7}$$

Where energy harvesting rate $\varepsilon_{har}(l)$ is given by [47] as:

$$\varepsilon_{har}(l) = \frac{1}{2} C_{cap} V_g^2 \left(2 \frac{\Delta Q}{V_g C_{cap}} exp\left(\frac{-\Delta Q}{V_g C_{cap}} n_{cycle}\right) - 2 \frac{\Delta Q}{V_g C_{cap}} exp\left(\frac{-\Delta Q}{V_g C_{cap}} n_{cycle}\right) \tag{8}$$

Above equation represents the energy harvesting rate, which is provided to nanodevices for harvesting vibrational energy [23] by the piezoelectric nanogenerators. In the above equation,

V_g -Represents the piezoelectric generator voltage,

C_{cap} -Denotes the capacitance of the ultra-nano capacitor.

ΔQ-Represents the electric charge harvested per cycle.

n_{cycle} -Denotes the rate of vibrational energy source.

Also, energy consumption rate $\varepsilon_{con}(l)$ rate is given by:

$$\varepsilon_{con(l)} = BR_l \times E_b(l) \tag{9}$$

Substituting equations 7, 9 in equation 6, we get:

$$\alpha(l) = \frac{\varepsilon_{har}(l)}{E_b(l)} \tag{10}$$

Since, we have already decreased $E_b(l)$, throughput of our routing protocol SLG is high.

B. *Mathematical analysis of IoNT network lifetime by SLG*

The lifetime of a network depends on the lifetime of critical nodes, i.e., the nodes which are essential for keeping the network paths alive. Based on the energy harvesting rate $\varepsilon_{har}(l)$, we can define the lifetime of the IoNT network. It is expressed as:

$$IoNT_{life} \infty \varepsilon_{har}(l) \tag{11}$$

This is because when the energy harvesting process stops for a node, only then can it be considered dead. When all the critical nodes die or in other words, stop harvesting energy, the IoNT network dies.

Since our routing protocol puts minimal pressure on the nodes, their energy levels are maintained at high levels, and therefore, the critical nodes do not die. The phases used in SLG make sure that the node that is low in energy be put to sleep or not be used for the forwarding purposes.

8. EXPERIMENTAL EVALUATION

Our simulation settings and parameters are listed in Table V. In every simulation; a decision is made dynamically in real-time whether to go for a single-hop communication or a multi-hop communication.

TABLE V. SIMULATION PARAMETERS [5]

Parameter	**Value**
Simulation tool used	NS3
Number of nano nodes	50
Number of nano routers	5
Number of gateways	1
Target area	20mm × 20mm
Band used	THz band
Packet Size	256 bits
E_{rec} at intermediate nodes	$\frac{1}{5} \times E_b(l)$
Number of simulations	50
Simulation time	50 seconds
Communication range of source node	150 nm
Communication range of nano router	500 nm
Communication range of gateway	1000 nm
Initial energy of source node	50 pJ
Initial energy of nano router	120 pJ
Initial energy of gateway	Unlimited

A. *Experimental Results*

This section describes the impact of SLG on energy consumption by nano nodes and the delay incurred in transmitting the packets. This analysis is presented in the next two sub-sections.

1) *Energy consumption:* Figure 11 shows the simulation results for the remaining energy of the source nodes. Two source nodes have been chosen randomly for this purpose. This residual energy is calculated against the number of transmission rounds conducted, i.e., a round in which at least one source node is trying to communicate with the nano router and the gateway.

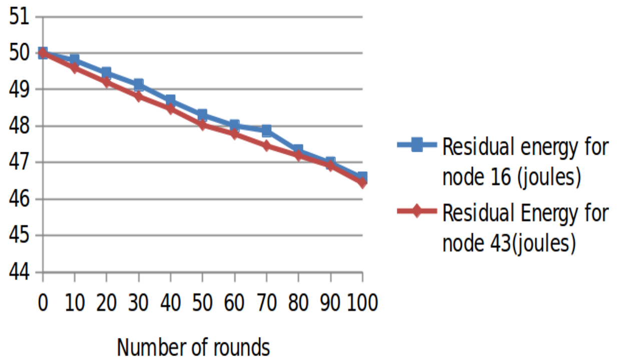

Figure 11. The Residual Energy of nodes Vs Number of Rounds

From the figure, it is clear that SLG is lightweight and does not put pressure of routing on the nano nodes.

2) *Delay:* The delay experienced by the nanodevice in IoNT has been analyzed for two scenarios: single-hop and multi-hop communication in a target area of 20 X 20 mm area as a function of distance from the nano router. The results are displayed in figure 12.

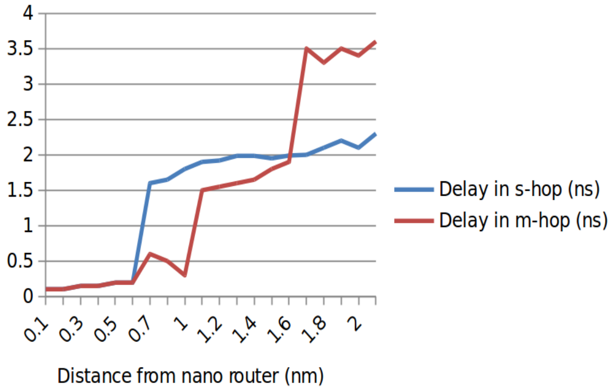

Figure 12. Delay in s-hop and m-hop Vs Distance from Nano Router

From figure-12, it is clear that up to a distance of 0.6 nm from the nano router, the delay has similar values for both s-hop and m-hop communications. This implies that the congestion does not have a preposterous impact on the packet delays over small distances but as the distance of the source node grows from the router, m-hop paths exhibit lesser amounts of delay in comparison to the s-hop paths. This decrease in delay for m-hop paths, however, continues only till the distance of nano source from the routers is less than 1.64 mm. After this point, the delay starts to increase for m-hop paths. This can be clarified by the fact that our experimental set-up has considered at most three intermediate nodes between the source and router. The problem must be that above 1.64 mm, the rising delay in retransmissions and receptions takes over the inherent advantage of small distances that the transmissions have to cover in m-hop communications. From this, we conclude that there is still a research opportunity for reducing the overall delay in the proposed routing protocol.

9. CONCLUSION AND FUTURE WORK

The central ideas of Nanotechnology can be utilized with any crude material, and its potential uses are restricted just by creativity, speculation, curiosity, research hours and investment. Main issues of IoNT were outlined, and it was realized that even though there is a long way to go before we can have synchronized and coordinated nano things, if the hardware-aligned and communication-focused studies are conducted in parallel; the true potential of IoNT, as well as IoMNT, will soon be grasped.

In this paper, we investigated various routing protocols proposed in the fields of WSN and IoNT and concluded that they cannot be used in the IoNT networks. The issue of routing requires immediate attention, given the fact that for any application to run, the nodes have to communicate consuming minimum energy owing to their energy-constrained nature. We explored this issue in this paper and proposed a novel routing protocol called SLG. It was analyzed mathematically that SLG gives high throughput, is lightweight and gives maximum IoNT network lifetime. Moreover, from the experimental evaluation, we concluded that there is still scope for reducing the delay incurred during the execution of IoNT routing procedures.

In this paper, we have not compared the SLG protocol with any other IoNT routing protocol. This is primarily for the reason that the literature available for IoNT routing is very scarce, and the ones existing as described in Table III are designed for static environments. We claim the supremacy of SLG protocol because it has been designed for the dynamic environment that exists in the IoNT. Moreover, the critical, mathematical, and simulation analysis of SLG orchestrate that it is a good fit for the IoNT networks.

In future, researchers can extend the work of further reducing the energy consumption of constrained IoNT nodes by maintaining the absolute time using a micro-scale device in the form of an illumination-clock that sends time and powers the energy-harvesting circuits of the nodes.

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Syed Rameem Zahra received the B. Tech. degree in Computer Science and Engineering from the University of Kashmir, Srinagar, J&K, India, and the M.Tech. Degree in Computer Science and Engineering from SMVDU, Katra, J&K, India. She is currently pursuing the Ph.D degree with the Department of Computer Science and Engineering, National Institute of Technology Srinagar, J&K, India. Her area of research is database systems, Wireless Sensor Networks, VANETs and IoT security.

Mohammad Ahsan Chishti has done his Bachelor of Engineering and M.S. in Computer and Information Engineering from International Islamic University Malaysia with specialization in Computer Networking. He has received his Ph.D. from National Institute of Technology Srinagar, India. Presently he is working as Assistant Professor in the Department of Computer Science & Engineering, National Institute of Technology Srinagar, India. He has more than 50 research publications to his credit and 12 patents with two granted International Patents. He is Senior Member-Institute of IEEE, Member IEI, Life Member CSI, and Member IETE. He is a certified White belt in Six Sigma by Six Sigma Advantage Inc. of USA (SSAI).