Energy Aware Routing Protocol for the Wireless Body Area Sensor Network (WBASN)

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Abstract—**IoNT has recently gained attraction for its twenty-four-hour capability in chronic disease monitoring as well as fatal event prognostics such as heart attacks. In IoNT, nanonetworks are connected to the internet via local gateways. In this paper, we propose a rational data delivery approach (RDDA) that addresses the challenges encountered in the IoNT paradigm. Two major features have been considered while realizing rationality (cognition) in this approach; these are reasoning and learning. Reasoning is used to determine and prioritize the characteristics of a given traffic flow and select the next hop for data transmission along the direction of the data flow. Whereas reasoning helps in realizing short term objectives and helping the network improve its current status, learning is used to accomplish long-term goals such as improving the lifetime of the network. The response obtained from the history of the network helps in the learning process and also helps in planning preemptive feedback. Hence, the proposed RDDA approach is energy efficient and is designed to enhance the current status of the nanonetwork, and thus, assure quality of information (QoI).**

Index Terms—**Internet of Nano-Things (IoNT), Energy-efficient, Routing, Wireless Body Area Sensor Network (WBASN) , communication layer stack.**

I. Introduction

IN risk management, nanotech has played a significant role in detection and containment of disasters [1]. In chemical engineering, for instance, carbon nanotubes have been used to sniff out dangerous and toxic gases; a network of these sensors can be laid out and used to monitor the motion of toxic gases over a large area [2]. In medicine, the existence of a disinfectant that works better and more efficiently than conventional traditional ones, by providing long-lasting anti-viral effect against major viruses, has proven the importance of nanosensing technology in disaster management [3]. The above-mentioned examples are just few of the many areas where nanosensing technology has made massive improvements. However, this technology is still suffering extreme limitations in terms of connectivity while collaborating in wireless network-based systems. IoNT stands out in terms of its distinctive features related to limited-energy constraints, short communication range in the THz band, and low processing power, and needs to be assimilated into the routing protocols to realize this new paradigm. Different challenges that face the data-routing process in IoNT are still being looked into, but a complete, effective solution has not been developed yet. Nanonetworks consume energy on all levels of their processes; they consume energy while sensing data, transmitting data, and processing data. Wireless multi-hop networks were used to achieve energy efficiency in such networks; consequently, adequate schemes have been proposed [4–7]. Nevertheless, such schemes end up being useless, unable to be used in real-life scenarios because they assume a static network topology [10–12], whereas nanonetworks show a haphazard network topology due to the mobility of the nanosensors' carrier or because they are restricted to two-hop routing schemes. Design and implementation of routing algorithms are considered imperative in nanonetworks. This is because nanonetworks' sensors are usually restricted in their processing power, communication range, and energy aptitudes.

The remainder of this paper is organized as follows. Section 2 reviews previous related studies. Section 3 discusses our system models. Section 4 describes our proposed routing approach for IoNT paradigm. Section 5 provides performance evaluation for the proposed approach. Finally, Section 6 provides the conclusions and future directions.

II. Related Work

The communication in nanonetworks can utilize one of the following technologies; nanomechanical, acoustic, electromagnetic, and chemical or molecular communication [8]. Mainly due to their tiny sizes, nanonetworks introduce difficulties in both hardware and software design. Especially for the software part, the communication layer stack needs fie tuning as such tiny hardware imposes critical restrictions. Knowing that the physical wireless signaling is performed at THz bands, due to the restricted antenna size, this necessitates special routing/communication techniques [9].

Routing protocols in nanonetworks can be classified into simple folding and random point-to-point protocols. These protocols can be optimized and customized for more efficient performance. However, several design aspects shall be taken in to consideration, such as the nanonetwork topology, nodes' mobility, deployment space (2D vs. 3D), and energy. In fact, energy is the most significant and limiting factor according to current nanotechnology studies [2]. In that sense, routing protocols, which optimize the energy consumption in nanonetworks while satisfying different constraints, are expected to have a great influence on the IoNT paradigm. Existing routing approaches in nanonetworks aim at extending the network lifetime by minimizing

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the energy consumption while considering traditional metrics which might not be effective in practice. In [16], authors proposed a peer-to-peer routing protocol. In their work, 2D uniform grids and 2D uniform random topologies are assumed, in which identical nanosensors are deployed. Packet collisions and redundant retransmissions are the only two metrics that have been considered while optimizing the proposed protocol. In this protocol, nodes are classified based on the packet reception statistics they have logged. The routing scheme exploits this classification in optimizing energy consumption. In [17], coordinate-based addressing scheme is proposed for nanosensors distributed uniformly in a rectangular 2D topology. The proposed routing protocol tries to minimize the hop count of the packet transmission by placing anchor nodes at the vertices of the grid. This routing protocol is assessed by considering packet retransmission rate, successful packet reception rate, and packet loss rate. In [18], channel-aware routing protocol is proposed. Authors considered the special attributes of the THz band communication. The forwarding is optimized by considering two cost factors: namely, avoiding long-distance region in which the signal may suffer the path loss and avoiding short-distance region in which the number of hops can be increased dramatically. However, their achieved results are based on simple 1D simulations. Authors in [19] focused on the physical layer part for their routing protocol. Thy proposed a physical network coding routing protocol by extending a geographical greedy routing algorithm for nanonetworks. The packets are separated into two parts and transmitted in pairs along pipelined multi-hop route, while avoiding grouped weak nodes to achieve energy effectiveness. The work presented in [20] proposes a geographic routing protocol; nodes of the nanonetworks are assumed to comprise two types of anchors, which have higher communication and processing capabilities than the edge nodes. NNA assumes that if a packet always follows shorter path, it will use the shortest path until it reaches destination node. In short, this algorithm uses four-direction transmission (left, right, up, down) only in virtual grid setups, where the closest vertical/horizontal but not diagonal relying on neighbor is used to send the data packet [14]. As a result, the hop count can unnecessarily increase and also the energy consumption is negatively affected by increased hop count. Meanwhile, in the shortest path approach (SPA), when a data packet is transmitted from a node it calculates the shortest path from the sender node to the destination instead of the node-to-node fashion. Accordingly, SPA uses eight-direction data forwarding (up, upper-left, upper-right, down, down-left, down-right, right and left), and thus, it considers the shortest path to destination rather than the shortest neighbor to relay. Nevertheless, nanosensors in the targeted IoNT can typically follow a random behavior. In this research, we proposed a rational data delivery algorithm (RDDA) as a distinguished routing protocol for the IoNT. It assumes a multitier nanonetwork and cluster/tierwide synchronization. Moreover, it's a topology-independent protocol which copes with the randomness nature in nanonetworks. According to RDDA, the system determines the path from the routing node (RN) to the destination node in view of each node's remaining energy. The remaining energy of recent RN's neighbors is controlled each time before a data packet is sent from the RN. If one of these neighboring RNs' energy is below half of the initial energy, a new alternative path will be determined and the data packet will be forwarded accordingly. Although this can increase the hop count in comparison to SPA, the energy efficiency will be improved and network lifetime will be prolonged.

III. System Models

IoNT in smart environments emerges to control physical/chemical changes and pass the information to sophisticated data centers for processing [23]. In smart environments, many parameters, such as pressure, temperature, sound, etc. One of the most important challenges is energy consumption. Therefore, an energy-efficient routing protocol is a key factor in prolonging the utilized nanonetwork lifetime dramatically. In the following section, we describe the assumed system model for the proposed RDDA approach.

A. Network Architecture

With the networking technology, nanosensors have more potential, since they can cooperate and communicate to achieve more challenging tasks. Figure 1 shows the general network architecture to be assumed in this paper for the vision of the IoNT paradigm. Significant elements of the nanonetworks are the nanosensors, NRs, and cognitive nanorouters (CNRs). Nanosensors are the smallest and simplest nanodevices. These devices can only perform simple computation tasks and can transmit over very short distances due to limited energy and memory and reduced communication capabilities. NRs have slightly larger computational resources than nanosensors, and thus can aggregate information. CNRs, also called nano-micro interfaces, are used to further aggregate the information forwarded by the NR and send them to a micro-scale device. And thus, CNRs are hybrid devices which can communicate in the nanoscale and can utilize classical communication paradigms in micro- and/or macrocommunication networks. Though

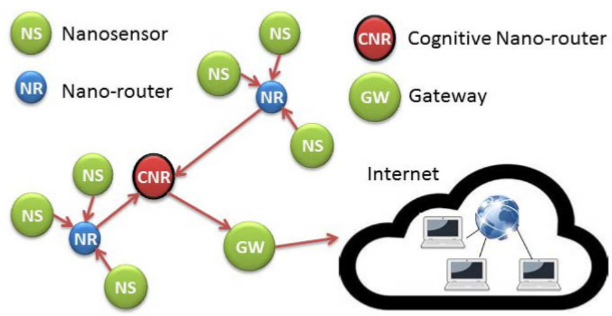

Fig. 1. Network architecture and main components in the IoNT.

GWs these types of networks can be connected to the traditional Internet. The communication range in IoNT is predicted to be between 1 nm and 1 cm in terahertz-band [24]. And thus, multi-hop routing is an effective data delivery style. Moreover, the direction of a communication route is not deterministic and depends on the drift velocity of nanosensors, which may result in service disruption and extended delays [25].

B. Lifetime in IoNT

Lifetime in this research is defied as the time or number of transmission rounds in which the nanonetwork can no longer send useful information to the end users. It is reflected by the network's inability to find a path to deliver data with satisfactory values for a number of QoI attributes such as latency, fairness, and remaining energy [21].Therefore, we can evaluate the lifetime of the nanonetwork in the IoNT by either counting the alive nanosensors [26], checking the ratio of still-covered areas to the uncovered ones by the nanonetwork, or based on both [27][28][29].

C. Energy Conservation and Dead Node Issue

Energy in nanonetworks can be a critical factor towards realizing the main objective of the emerged IoNT paradigm. Knowing that majority of the nanonetwork energy budget is spent on routing data, we focus this study on the NR energy expenditures. According to [24] this can be characterized by the following equation.

$$E_{N\ R} = C\left(T\ *\left(E_{T\ X}\right) + R\ *\left(E_{R\ X}\right)\right) \tag{1}$$

where $E_{T\ X}$ and $E_{R\ X}$ are transmission and reception energy, respectively. C indicates the cost function of the energy consumed, and T and R are the number of transmitted and received packets, respectively. As discussed earlier, the main function of CNR is data aggregation and routing of traff received from the NRs. Therefore, it is expected that CNRs consume additional energy compared to regular NRs. This energy consumption can be characterized as follows:

$$\mathrm{E}_{C\ N\ R} = C\left(T\ *\left(E_{T\ X}\right) + R\ *\left(E_{R\ X}\right)\right) + C\left(A\ *\left(E_{a\ g}\right)\right) + C\left(P\ *\left(E_{c\ g} - E_{p\ m}\right)\right) \tag{2}$$

In Eq. (2), A and P, represents the total number of packets that are aggregated and processed by the cognitive nanorouters, respectively. $C\left(A\ *\left(E_{e_z}\right)\right)$ shows the energy cost during data aggregation, and $C\left(P\ *\left(E_{\alpha_g} - E_{p\ r\ o}\right)\right)$ reveals the energy cost due to protocol and processing overhead while performing cognitive (rational) processes. By forming Eq. (2) in terms of the energy cost of NRs we obtain:

$$\mathrm{E}_{C\ \mathrm{VR}} \geq E_{N\ R} + C\left(A\ *\left(E_{\mathrm{g}}\right) + C\left(E_{\alpha_{\mathrm{g}}} - E_{p\ v}\right)\right) \tag{3}$$

If the NR and CNRs use the same transmit power, the equality sign becomes positive in Eq. (3). In this study, we assume multi-tier NRs' distribution. Once all the fist tier NRs are dead, no other node will be able to send data to the GW, and the lifetime of the network will be over.

IV. Rational Data Delivery Framework

In this section we propose a novel rational data delivery approach (RDDA) for the IoNT paradigm. Assume x is a randomly selected nanosensor by the GW based on the required data in a specific IoNT application. The random number of relays within the communication range of the nanosensor x can be modeled by a spatial Poisson process X[30] . Assume that the nanosensor x can be at point $z \in R^2$ and $l(z,\ X)$ is the shortest distance from z to the nearest point of X such that $l(z,\ X) \leq r$ since X is a spatial Poisson process, then $l(z,\ X) \leq r$, if and only if $NR(d(z,\ r)) > 0$ where $d(z,\ r)$ is a disc of radius r centered at z . And $N\ R(d(z,\ r))$ is a Poisson random variable denoting the number of nanorouters within the disk $d(z,\ r)$ with remaining energy sufficient to transmit at least once. Consequently, the probability of having at least one NR neighbor within the transmission range of the nanosensor x is given as follows.

$$P(l(z,\ X) \leq r) = P(N\ R(d(z,\ r)) > 0) \tag{4}$$

In this study, it is assumed that the nanonetwork is dead when the lifetime of the neighboring NRs is expired. Thus, assuming $f\left(x_j\right)$ is the cost function of transmitting from $\mathrm{NR_j}$ to GW in terms of fairness, $g(x)$ is the energy of neighboring NRs, $b(x)$ is the minimum distance from a neighbor $\mathrm{NR_j}$ to GW, $i(x)$ initial energy of the neighboring NR. Accordingly, the RDDA framework assumes three main criteria for data routing; (1) evaluation criteria; $f\left(x_j\right) =$ cost(Neighbor NR to GW) and $b\left(x_j\right) = \min\ \left(f\left(x_j\right)\right)$, this is guaranteed by lines 11 to 18 in Algorithm 5.1, (2) selection criteria; $g\left(b\left(x_j\right)\right) > i\left(b\left(x_j\right)\right)\ *\ 50\ \%$, is found between lines 19 and 21, and (3) termination criteria; all one-hop NR s are dead or $P(l(z,\ X) \leq r) = 0$.

In Algorithm 5.1, rational (cognitive) elements such as reasoning and learning are applied at the CNR. In the following a detailed description about these elements is provided.

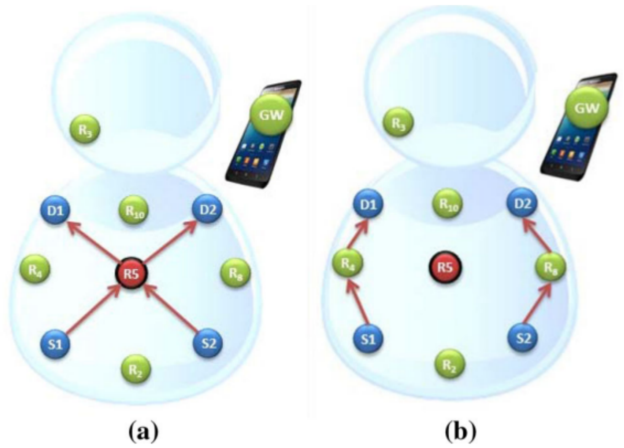

Fig. 2. (a) Typical routing and (b) rational routing in the IoNT.

A. Learning

Learning is used in our RDDA approach in order to identify the most appropriate routes toward the Internet gateway while maintaining several QoI attributes in the nanonetwork, such as fairness, delay, and energy-efficiency. Via learning, each time a CNR has to choose an NR on the route, it excludes NRs which can increase the cost in terms of QoI attributes between the current NR and the gateway. Positions of those NRs which best fi the required QoI in a nanonetwork are saved in the CNR for future use as well. This, the direction, along with the destination feedback about the chosen path, helps the CNRs to learn and improve paths toward destinations in the IoNT. In the following, we elaborate more on this cognitive feature/element through an illustrative example.

Example 1 . Let's assume we have n nanorouter, where the ith available router $R_i \in \{R_I, R_2, \ldots, R_n\}$. S_t and S_2 have a data packet to be sent to destination devices D_1 and D_{z*} Out of these relays, it is determined that R_5 provides the lowest cost to D_l and D_2 as shown in Figure $2(\mathrm{a})$. Therefore, S_I sends the data packet to R_5 . And S_2 sends its data packets to R_5, as well. As a result, the route through R_5 becomes congested and packets start dropping and get lost. But with a rational nanonetwork employed with learning elements, congested routes can be identified and avoided by observing the aforementioned Qol attributes. It can respond to undesired scenarios proactively, by routing the data through a different path consisting of R_6, and R_g, as shown in Figure 2 (b).

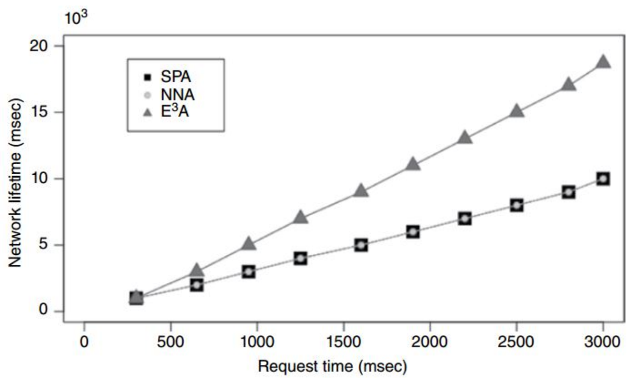

Fig. 3. (a) Typical routing and (b) rational routing in the IoNT.

B. Reasoning

In the RDDA algorithm, we also employ the reasoning element for more rational nanonetworks. A modified version of the analytic hierarchy process (AHP) [31] is considered in order to implement this element of cognition in the IoNT. The reason we choose AHP for reasoning is that it supports multiple-criteria decision-making while deciding on which path to deliver. For example, if we have imbalance in selecting the next hop for data delivery in energy-constrained nanonetwork, the set of NRs which provides the lowest energy consumption while satisfying the fairness attribute will be chosen even though it might degrade other metrics such as the network delay or cost. This means fairness and energy are prioritized over cost and delay in this situation. If two alternative paths can guarantee the same in terms of fairness and energy, then the next attribute to compare will be delayed, followed by the cost. The assumed AHP algorithm provides a method for pairwise comparison of each of the aforementioned attributes and helps to choose the node that can provide the best network performance in the long run.

V. Performance Evaluation

In this section, we evaluate the performance of the proposed RDDA against the two routing categories of the nanorouting approaches in the literature, namely the SPA and NNA algorithms. Based on the aforementioned system models, we summarize these two baselines' as follows. This, we compare our proposed RDDA with both NNA and SPA in this research. A detailed description of our experimental setup is given in the following section.

A. Experimental Setup

In this section, a detailed description of the performed experiment for validation and verification purposes has been introduced. In addition to computer-based simulations, real sensing/relaying devices have been used in a test-bed for practical verifications. . The use of TI CC2530 programmable motes [32] has enabled a fie-tuned programming, with a more sophisticated base for carrying out tasks that require high-end processors and devices.

We used NS3 as simulation tool for this purpose as well. The simulation is processed in three platforms, which are Windows, Linux, and OSX, for validation purposes. We executed our simulation 100 times for each experiment and plotted the average results. More details about our simulation are summarized in Table I.

B. Simulation Results

According to our previous discussion, we assume, as seen from Figure 4 that we have $36\,\mathrm{NRs}$ and $1\,\mathrm{GW}$ in an area of $1000\,\mathrm{nm} \times 1000\,\mathrm{nm}$. Each RN is linked to a set of adjacent RNs, which are connected in all directions. In Figure 4, we can see small and big circles denoting the NRs' and GW's range, respectively, where the GW can scope any NR which exists in its circle. Moreover, the connections between GW and NRs are bidirectional. Accordingly, the GW in Figure 5 has

bidirectional connections with the closest NR14, NR15, NR20 and NR21; additionally, the GW has unidirectional connection with the other NRs which are located in its vicinity.

The comparison between the two main baselines, SPA and NNA against RDDA approach, is depicted in Figure 6. Paths which connect NRs to the GW changes over the lifespan of the nanonetwork based on the remaining energy in each NR. Consequently, the average hop count changes, and it's important to note that this number of hops is proportionally related to the average packet delay. Therefore, the higher the number of hop count, the higher the delay. Inferring from the graphs

TABLE I
SIMULATION PARAMETERS AND VALUES BASED ON [26]

Parameter	Value
Target area	100 nm × 100 nm
Number of nodes	SNs: 1500, NRs: 36, GW: 1
Communication Range	SN: 130 $n\ m$, NR: 200 $n\ m$, GW: 400 $n\ m$
Initial Energy	SN: 31000 , NR: 110000 , GW: Unlimited
Energy Consumption	SN and NR (Receiving): 31.2 uJ/bit SN and NR (Transmitting): 53.8 uJ/bit

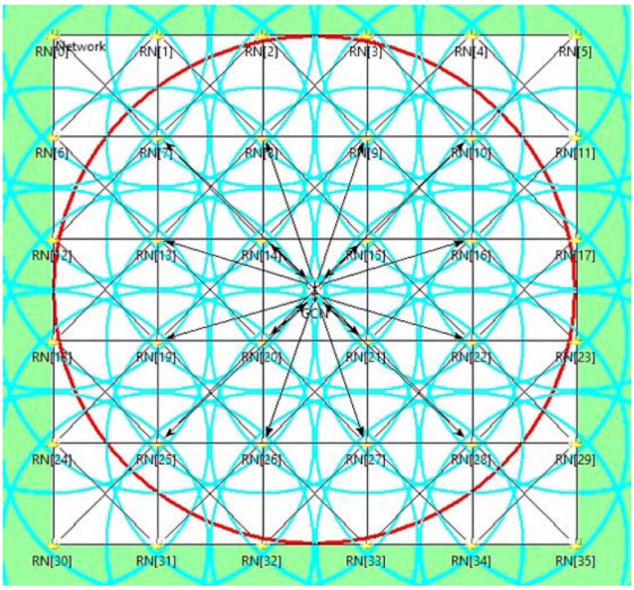

Fig. 4. Assumed nanonetwork topology.

in Figure 6, we observe that the number of hops has an inverse relationship with the lifetime measured in rounds. The more rounds a nanonetwork experience, the fewer hops it should use. By comparing SPA, NNA, and RDDA in all instances, the number of hops is always less when RDDA is applied, which is a desired feature toward reducing delay and energy consumption.

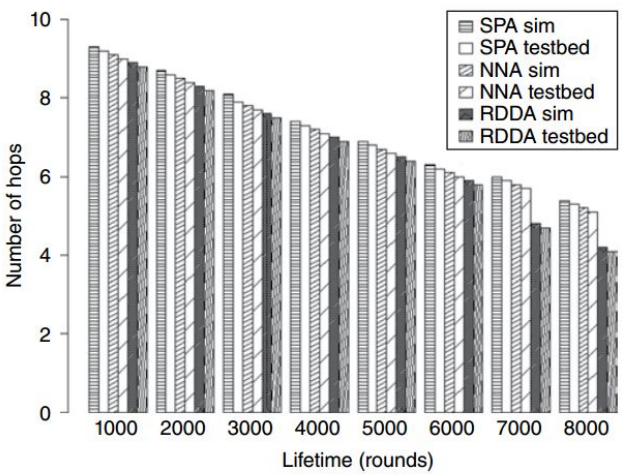

Fig. 5. Number of hops vs. lifetime.

From Figure 5 we can also deduce also that when lifetime is relatively long (more than 6000 rounds), RDDA approach becomes more effective. From Figure 6, we can clearly see that the latency for SPA is higher than any other approach. This is because it determines the path to be followed by packets using the energy level of the nearest NRs (or next hop) only. On the other hand, RDDA has the least delay.

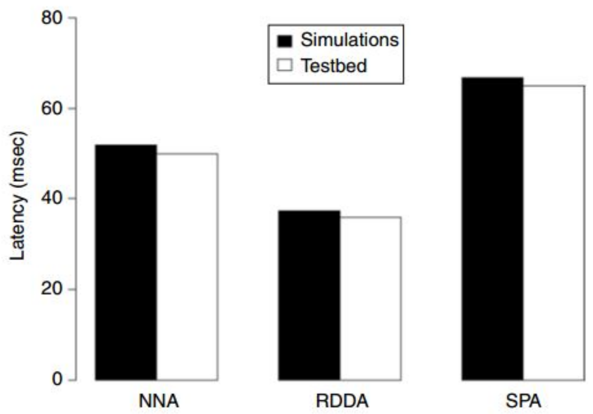

Fig. 6. Comparison of latency.

Figure 7 shows the average energy levels per round. We can conclude from the figure that RDDA is the best and most efficient in terms of energy compared to the other baselines. RDDA saves 5 % more than SPA, and 16.85 % more than the NNA algorithm in terms of energy.

Figure 8 shows the lifetime of the network for the three baseline algorithms. The X-axis shows the different types of the network algorithms, while the Y-axis shows the lifetime in seconds. From the graph, we observe that RDDA has extended lifetime, while NNA and SPA achieve almost the same lifetime span. RDDA exceeds the other two algorithms by 562100 seconds. Figure 9 shows how the lifetime of the system is affcted by the requests made by the GW. Th X-axis shows the request time in seconds, while the Y-axis shows the network lifetime in seconds. From the figure, we can see that the lifetime of the system increases with the increase of request time. Obviously, the lifetime of both SPA and NNA are less than the achieved lifetime by RDDA. Hence, we conclude that the increase in request time of the GW can increase

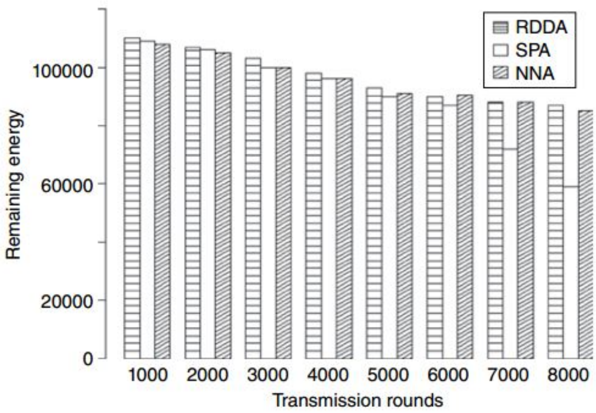

Fig. 7. Comparison of average energy level at NRs vs. transmission rounds.

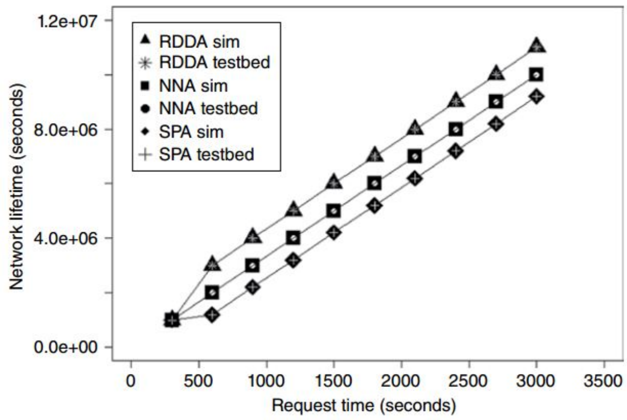

Fig. 9. Comparison of network lifetime according to GW's request time.

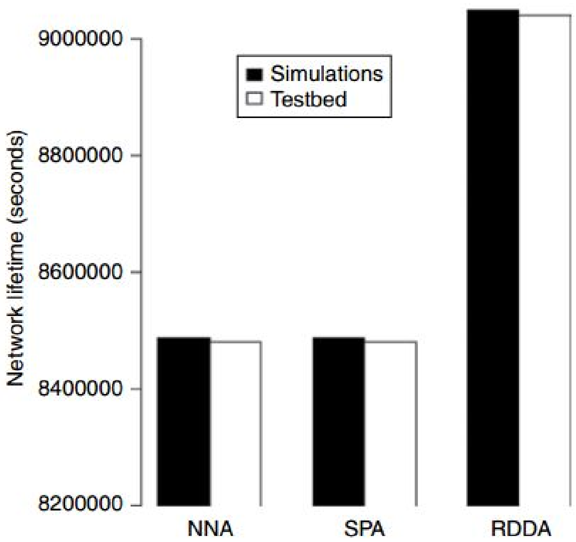

Fig. 8. Comparison of average energy level at NRs vs. transmission rounds.

the lifetime of the nanonetwork.
Figure 10 depicts the comparison of a one-hop energy level from the GW. The X-axis shows the GW nearby NRs[13], while the Y-axis shows the energy level of a given NRs. NR[14], NR[15], NR[20], and NR[21] are chosen specifically because they have bidirectional connection with the GW and will be the most stressed nodes in the nanonetwork as they are the closest to the GW and must be used in any communication with it. Comparing the energy levels under the three different routing approaches, we notice that although the energy levels for NNA and SPA are the same in NR[14], NR[15], NR[20], and NR[21], RDDA is diffrent and outperforms all of them. And thus, RDDA increases the network lifetime, and it is much better in terms of energy saving.
In Figure 11 we examine the fairness level in each of the applied routing approaches. We define fairness as the ability of the system to echo the energy exhaustion rate at each nanosensor by redistributing the load over all the available NRs. That is because the IoNT paradigm is supposed to handle multiple resources under different restrictions and energy constraints. In this figure, we observe that the fairness of RDDA is more than that of the other two alternatives. The main reason for these results is that RDDA uses the aforementioned learning and reasoning elements in deciding the next hop, and hence, the processed requests are evenly distributed among the available NRs.

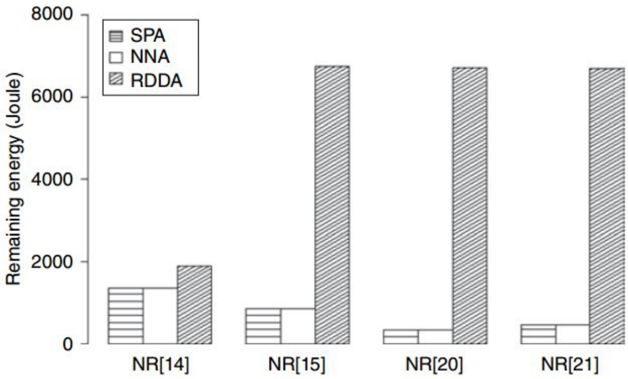

Fig. 10. Comparison of one-hop NRs' energy level.

VI. Conclusions

In this research, we examined two different categories of routing methods in the IoNT paradigm, namely the SPA and NNA, in terms of energy consumption, delay, and fairness. We proposed the RDDA approach, which is unique in prolonging the nanonetwork lifetime without violating other QoI attributes in IoNT. We concluded that RDDA can save a significant amount of energy. Additionally, this approach reduces the number of hop counts by roughly 23%. This is a significant achievement, especially when we learn that nanonetwork lifetime has an inverse relationship with the hop count. Furthermore, we explained how the hop count can be used to show on-spot and average delays at NRs. Moreover, we demonstrated how the RDDA approach provided the longest network lifetime. Even though both SPA and NNA demonstrate that they are efficient in terms of transmission rounds and energy consumption, the general results show that RDDA outperforms both of them.

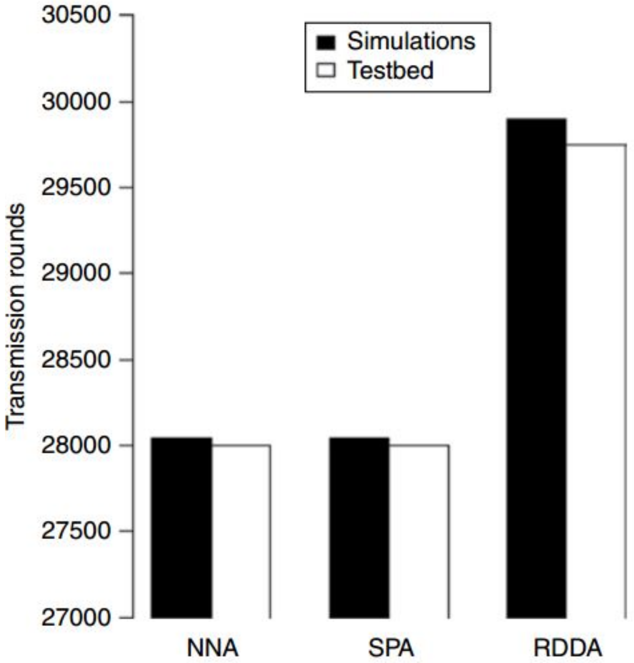

Fig. 11. Comparison of the three data delivery techniques based on total number of transmissions.

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