

Received May 10, 2020, accepted May 21, 2020, date of publication May 26, 2020, date of current version June 8, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2997635

# An Efficient Routing Scheme for Intrabody Nanonetworks Using Artificial Bee Colony Algorithm

HAMZA FAHIM<sup>1,3</sup>, SHUMAILA JAVAID<sup>2,3</sup>, WEI LI<sup>1</sup>,  
ISMAIL BEN MABROUK<sup>4</sup>, (Senior Member, IEEE),  
MUATH AL HASAN<sup>4</sup>, (Senior Member, IEEE), AND  
MUHAMMAD BABAR RASHEED<sup>5</sup>, (Member, IEEE)

<sup>1</sup>School of Electronics and Information, Xi'an Jiaotong University, Xi'an 710049, China

<sup>2</sup>School of Computer Science, Shaanxi Normal University, Xi'an 710062, China

<sup>3</sup>Department of Computer Science, COMSATS University Islamabad, Islamabad 45550, Pakistan

<sup>4</sup>Networks and Communication Engineering Department, Al Ain University, Abu Dhabi, United Arab Emirates

<sup>5</sup>Department of Electronics and Electrical Systems, The University of Lahore, Lahore 54000, Pakistan

Corresponding authors: Wei Li (liw@xjtu.edu.cn) and Muhammad Babar Rasheed (babarmeher@gmail.com)

This work was supported by the Abu Dhabi Award for Research Excellence under Grant AARE19-245.

**ABSTRACT** An Intrabody Nanonetwork (IBNN) is constituted by nanoscale devices that are implanted inside the human body for monitoring of physiological parameters for disease diagnosis and treatment purposes. The extraordinary accuracy and precision of these nanoscale devices in cellular level disease diagnosis and drug delivery are envisioned to advance the traditional healthcare system. However, the feature constraints of these nanoscale devices, such as inadequate energy resources, topology-unawareness, and limited computational power, challenges the development of energy-efficient routing protocol for IBNNs. The presented work concentrates on the primary limitations and responsibilities of IBNNs and designs a routing protocol that incorporates characteristics of Exponential Weighted Moving Average (EWMA) Based Opportunistic Data Transmission (EWMA-ODT) and Artificial Colony Algorithm Based Query Response Transmission (ABC-QRT) approaches for efficiently handling the routing challenges of IBNNs. In EWMA-ODT, the moving Nano Biosensors (NBSs) employ the EWMA method attributes to aggregate detected data by assigning high weightage to the recent detected information. Later, the aggregated data is transmitted to the Nano Router (NR) when the direct data transmission opportunity is available, the reception of aggregated briefs NR about the condition of the network after the last successful interaction with minimum energy consumption. Whereas, the ABC-QRT approach introduces the ABC algorithm for the selection of those optimal NBSs that have maximum fitness value for satisfying the data transmission demand of the external healthcare system with minimal traffic overhead. The simulation results validate that the joint contribution of these approaches enhances IBNNs lifetime and reduces end-to-end delay as compared to the flooding scheme.

**INDEX TERMS** Artificial bee colony algorithm, nano router, exponential weighted moving average, intra-body nano-networks, routing protocol.

## I. INTRODUCTION

The advancement of nanotechnology has boosted the development of nanoscale devices [1], which are remarkably transforming medicine and the healthcare system. These nanoscale devices have outstanding characteristics for non-invasive disease detection, diagnosis, and treatment at the cellular level. In an Intrabody Nanonetwork (IBNN), nanoscale devices

are implanted inside the human body for continuous monitoring of vital body parameters and tuning medical treatments [1], [2]. The scope of IBNNs is envisioned to advance nanomedicine applications such as early detection of cancer cells, detecting kidney damage, repairing damaged cells, and delivering drugs, heat, or light to the specific types of cells (such as cancer cells) [3], [4].

The implanted nanoscale devices are equipped with graphene-based nanoantennas that radiate Electromagnetic (EM) waves in the Terahertz (THz) band with extremely

The associate editor coordinating the review of this manuscript and approving it for publication was Chien-Fu Cheng.

high bit rates [2]. EM-based intrabody communication enables Nano Biosensors (NBSs) to work in a distributed manner for accomplishing specific goals. However, the nano-size of these implanted devices along with the communication challenges in the THz band (such as channel modeling in the THz band and molecular absorption noise) are the fundamental limitations that require serious attention [5], [6]. The extreme constraints of NBSs compared to the microsensors can be described as; with the inadequate energy resources of NBSs, they can transmit only a limited number of messages (i.e., approximately ten packets of 200 bits with the maximum energy they may harvest). Whereas, in the context of storage, NBSs do not have enough storage resources available for storing routing information; therefore, the selection of the next optimal forwarding hop is nearly impossible. Thus, the extreme feature constraints of NBSs require novel communication protocols for IBNNs that can handle the frequent physiological data transmission pressure from the external healthcare system for effective diagnosis and treatment of patients without sharp depletion of energy resources of IBNNs [7].

Over the past decade, a growing interest has been witnessed for the development of novel EM-based communication schemes [4], [8]–[12]. The flooding scheme proposed in [13], conserves the energy resources of NBSs by regulating forwarded data flow. In another scheme [11], the rapid depletion of energy resources is prevented by employing the greedy scheme. The greedy scheme selects a single NBS with the maximum energy for generating a response message to the Nano Router (NR) for saving energy resources. The energy conservation scheme proposed in [8] prolonged the lifetime of IBNNs by introducing nanocontrollers for data collection. Direct data transmission to nanocontroller supported in conserving energy resources. In [14], the presented work investigated the energy harvesting options available for enhancing the life span of NBSs. In another routing scheme presented in [9], introduced fuzzy logic and bio-inspired based NBSs selection for reducing complexity during the selection of NBSs. NBSs selection based on fitness value resulted in improved network lifetime. However, since the development of novel approaches for enabling energy-efficient communication in IBNNs are in the early stages; therefore, more efforts are required.

In the presented work, the proposed novel routing scheme explicitly concentrates on the challenges of IBNNs by taking into account the fundamental disparity between the communication load and limited available resources of NBSs. In line with the vast applicability of bio-inspired solutions such as swarm intelligence algorithms for low energy and computational devices [15]–[17], they have been used in various applications, including energy-efficient clustering [18]–[20], node localization [21], [22], and improved data collection [23] in wireless sensor networks. Moreover, in the context of the internet of things and vehicular ad-hoc networks, bio-inspired routing techniques efficiently handle the frequently changing topology issues and enable the design

of low complexity routing protocols [24], [25]. The presented scheme also employs the characteristics of the Artificial Bee Colony (ABC) algorithm that optimizes the fitness function for the selection of NBSs for improving the performance of IBNNs in terms of residual energy, end-to-end delay, and packet delivery ratio. In addition, the introduction of Exponential Weighted Moving Average (EWMA) in our proposed scheme improves diagnosis and treatment due to the characteristics of the EWMA approach for real-time monitoring applications [26]–[30]. Accordingly, the introduction of EWMA- Based Opportunistic Data Transmission (EWMA-ODT) and ABC algorithm - Based Query-Response Transmission (ABC-QRT) schemes in our proposed novel routing scheme achieves the ultimate objective of data collection with minimum delay and energy consumption. To the best of our knowledge, to date, no existing scheme has considered EWMA-based and ABC-based data aggregation in IBNNs. This is the first work that joins the characteristics of these approaches to design a powerful data collection mechanism for resource constrain IBNNs. The main contributions of our proposed scheme are underlined below:

- 1) Our proposed EWMA-ODT approach exploits NBSs mobility and EWMA-based data aggregation method for saving energy resources and facilitating topology-unaware characteristics of NBSs by transmitting data when an NR is found in the direct transmission range of NBSs. Using this approach, EWMA-ODT increases the probability of direct data transmission that is highly desirable for resource constraint IBNNs. Whereas, the low complexity EWMA approach combines the previously detected readings with the fresh reading, while the transmission of this EWMA-based aggregated data packet briefs NR about the state of physiological parameters after the last successful interaction with minimum data storage burden.
- 2) ABC-QBT approach focuses on the need for instant response messages transmission with minimum delay and energy consumption. ABC algorithm nominates NBSs for generating response messages based on their fitness value. The proposed fitness criteria avoid redundant data transmission and prevent energy exhaustion of those NBSs, which have low residual energy.
- 3) We present the detailed energy consumption analysis of our proposed scheme. Moreover, we evaluate and compare the proposed scheme with the flooding scheme using the Nano-SIM tool to highlight the performance impact of our proposed scheme.

The rest of the paper is organized as follows. In section II, we discuss the system architecture and proposed work in detail. Section III comprehensively demonstrates energy analysis of our proposed work. Section IV presents the performance evaluation, simulation results, and discussion of the proposed routing scheme. In Section V, we finally draw up the conclusion.

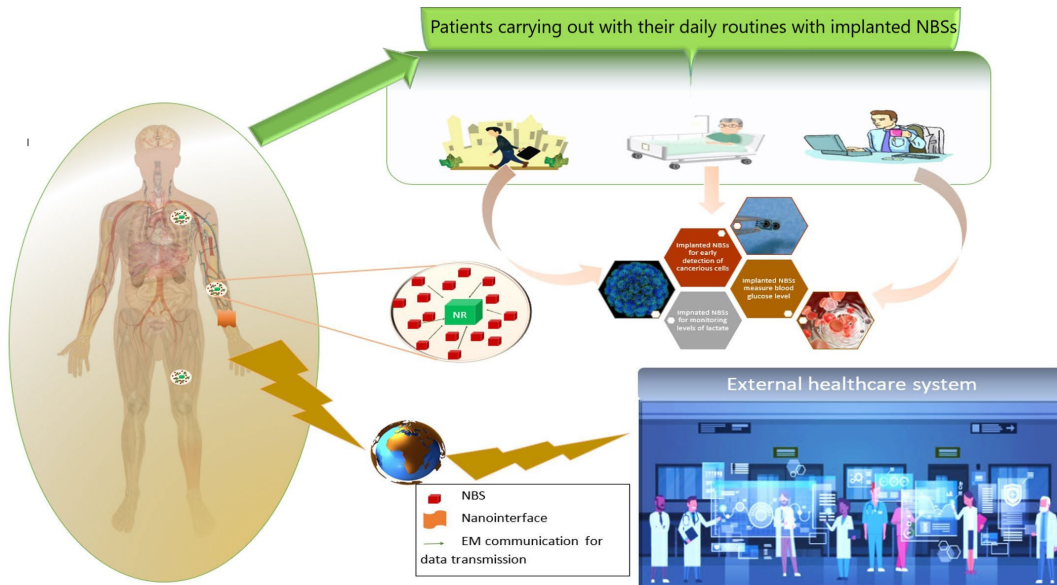


FIGURE 1. An overview of the system architecture constituting an IBNN and external healthcare system.

## II. EXPONENTIAL WEIGHTED MOVING AVERAGE AND ARTIFICIAL BEE COLONY ALGORITHM FOR DESIGNING ENERGY CONSERVING ROUTING SCHEME

In this section, we provide a detailed demonstration of our proposed routing scheme, including system architecture, network model, and a comprehensive description of the proposed routing protocol.

### A. SYSTEM ARCHITECTURE

The considered IBNN is constituted of nanoscale devices, namely NBSs and NRs. Intrabody communication among the nanoscale devices is enabled by graphene-based nano-antennas that radiate EM waves in the THz band. NBSs are assumed to have more critical resources in terms of energy, storage, and computational power as compared to NRs. Therefore, NBSs perform low complexity operations (such as event detection, simple computational operations, and transmission) to enhance the lifetime of IBNN. In contrast, NRs have enough resources for data aggregation from implanted NBSs and later transmission to the external healthcare system using nanointerface. Nanointerface provides connectivity between IBNN and remote healthcare system using IEEE 802.15.4 radios. The interaction between IBNN and the external healthcare system can be carried out on the demand of the external healthcare system or also in a periodic manner. A possible system architecture is further demonstrated using Fig. 1.

### B. NETWORK MODEL AND ASSUMPTION

In the proposed protocol, the network topology of considered IBNN is described as an undirected graph  $G = (V, E)$ .  $V$  represents the set of NBSs and NRs expressed as  $\{(ns, nr) \in V\}$ . The considered network model is based on the following assumptions:

- 1) The positions of the NRs are fixed while NBSs are maintaining a mobile motion in the network.
- 2) TS-OOK modulation scheme is adapted at the physical layer, TS-OOK modulation scheme is similar to the impulse radio ultra-wideband (IR-UWB) technology, capable of accurately locating NBSs position by broadcasting a simple message.
- 3) The energy consumption model mainly considers packet transmission and reception as the primary causes of energy consumption.

### C. PROPOSED PROTOCOL DESCRIPTION

In this section, we provide a detailed description of our proposed scheme that incorporates EWMA-ODT and ABC-QBT approaches; the complete demonstration of the proposed scheme is also visually represented using Fig. 2 to provide a detailed elaboration of our proposed scheme.

#### 1) EWMA-BASED OPPORTUNISTIC DATA TRANSMISSION (EWMA-ODT) APPROACH

Our proposed EWMA-ODT emphasized saving energy resources that are consumed in the transmission of redundant data and multi-hop forwarding. To achieve this objective, opportunistic data transmission exploits the moving nature of NBSs for transmitting the stored reading to the NR during an occasional interaction. Using this approach, NBSs can save their limited resources that are consumed in the labors' task of frequent data transmission. The working of the proposed scheme is outlined as follows:

- 1) *EWMA-based detected event aggregation*: Implanted NBS detect event at different time stamps and perform a low complexity EWMA approach to combine the detected readings. NBSs store the combined readings in their buffer and transmit it whenever a successful interaction occurs.

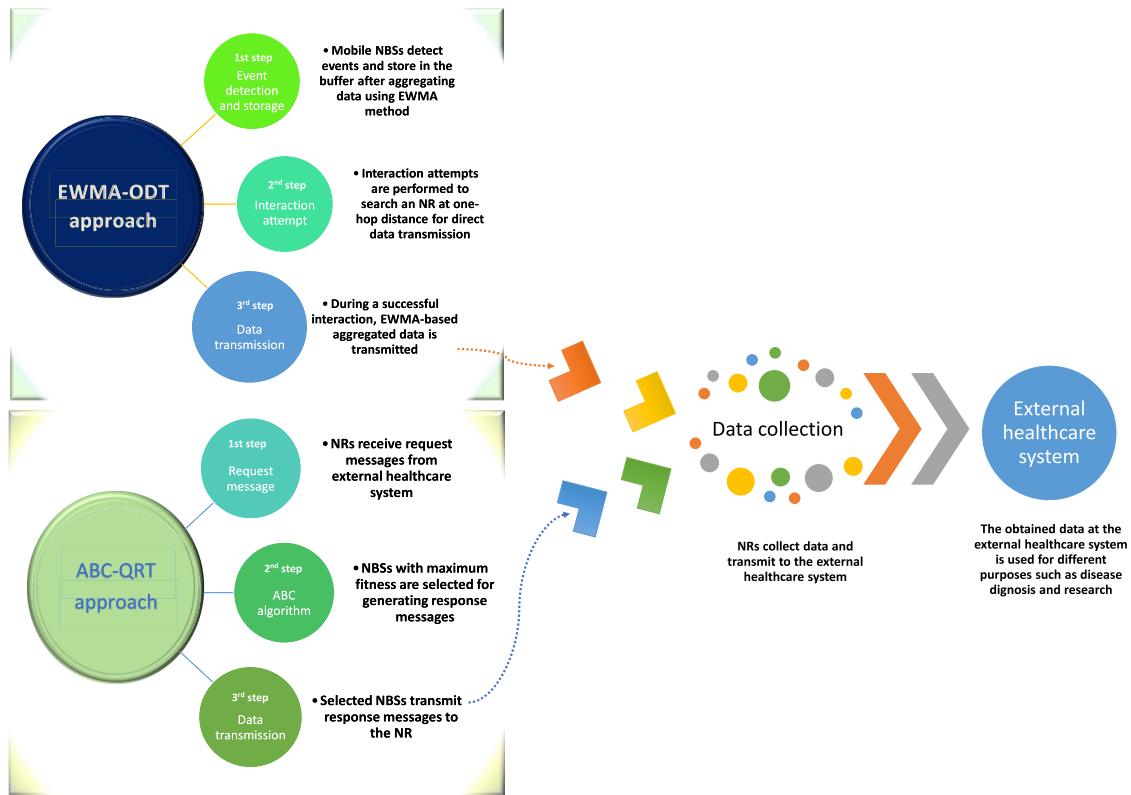


FIGURE 2. A brief overview of the proposed scheme incorporating EWMA-ODT and ABC-QRT approaches.

**Definition 1:** Data reading observed by a NBS  $NBS_i \in NBS$  at different points of time can be expressed as  $\{r_1^{t(1)}, r_2^{t(2)}, \dots, r_n^{t(n)}\}$ . NBS combines the current observed reading  $r_n^{t(n)}$  with the previous readings  $r_{n-1}^{t(n-1)}$  until it has a successful interaction with the NR. The aggregation of detected readings using EWMA is given in (1):

$$AggregatedValue = \omega(r_n^{t(n)}) + (1 - \omega)(r_{n-1}^{t(n-1)}) \quad (1)$$

where  $r_n^{t(n)}$  and  $(r_{n-1}^{t(n-1)})$  are the reading observed at time instances  $t(n)$  and  $t(n - 1)$ , respectively. While the value of  $\omega \in [0, 1]$  is used for smoothing the consequences of past trends. The greater weight to  $\omega$  significantly influences the latest readings in comparison to past readings.

Employing the EWMA approach in real-time healthcare monitoring applications assigns more weight to recent observations, which considerably improves diagnosis and treatment.

- 2) **Data transmission:** During the lifespan of NBSs, it makes  $n$  interaction attempts to transmit data expressed as  $\sum_i^n (IA)$ . Whenever an interaction attempt is successful (i.e., a moving NBS finds an NR in its transmission radius), it transmits the data packet to the NR. The reception of EWMA-based aggregated data packet represents the condition of the network sampled

at different points in time, denoted by,  $DP(Nbit)_{\Delta t}^{Agg}$ ; where  $DP(Nbit)_{\Delta t}^{Agg}$  is the aggregated data packet with  $Nbits$  from the last interaction time to the latest interaction time. The direct transmission from the sender to received avoids multi-hop data aggregation and reduces forwarding data overhead.

#### D. ABC ALGORITHM-BASED QUERY-RESPONSE TRANSMISSION (ABC-QRT)

The objective of the ABC-QRT approach is to satisfy the instant requirement of data transmission to the external healthcare system with minimum energy consumption and delay. Our introduced ABC algorithm-based NBSs selection mechanism encourages the selection of optimal NBSs for generating response messages to avoid redundant data traffic overhead. ABC algorithm is a swarm-based artificial intelligence algorithm [31], which is inspired by the foraging behavior of honey bees. ABC algorithm encompasses three bee groups; onlooker, scouts, and employed bees, where each bee represents a position in the search space. The employed bee visits the previously visited food source, and scouts carry a random search. The position of the food source briefs about the possible solution to an optimization problem. Whereas, the amount of nectar represents the fitness of the associate solution. In the ABC algorithm, the first location of the food source is randomly generated by nominating employed bees

**Algorithm 1** EWMA-Based Opportunistic Data Transmission (EWMA-ODT) Approach

- 1: Set of NBS  $\{ns\} = \{ns_1, ns_2, ns_3 \dots ns_n\}$
- 2: Set of NRs  $\{nr\} = \{nr_1, nr_2, nr_3 \dots nr_n\}$
- 3: **Action:**
- 4: **For** each NBS  $ns_i$  do
- 5: **If** (NR is in transmission radius of NBS)
- 6: Transmit the EWMA-based aggregated data
- 7: Empty buffer
- 8: **Else**
- 9: Aggregate the reading using EWMA method given in Equation (1)
- 10: Store in buffer
- 11: **End If**
- 12: **End For**

to a different food source; the new food source is determined by using (2):

$$v_{x,y} = W_{x,y} + \chi_{x,y} \times (W_{x,y} - W_{z,y}) \quad (2)$$

where  $\chi_{x,y} = \text{random}(-1, 1)$ ,  $W_k$  is a neighbor solution,  $y \in \{1, 2 \dots D\}$  is a randomly chosen parameter index. D is the dimension of the solution vector.

Later, each employee bee searches for a new food source that is associated with its current food source. The nectar amount is computed for each iteration, accordingly if the new nectar amount has better quality (fitness) than the previous one, then employed bees move to the new force and abandon the precious. Whereas, if the new source does not have a higher nectar amount, then they continue with the old one. Employee bees share the updated information about food sources with the onlooker bees after completion of the search process. Onlooker bee evaluates the fitness of nectar and selects a food source according to the probability given by (3); this selection method increases the chance of selection of the candidate that has the highest fitness value.

$$p_x = \frac{f(X_x)}{\sum_{n=1}^{SN} f(X_n)} \quad (3)$$

where the  $x^{th}$  food source position is represented as  $X_x = \{x_{x1}, x_{x2} \dots x_{xD}\}$  and the fitness of the food source located at  $X_x$  is  $f(X_x)$ . Once food sources are selected, each onlooker searches for a new neighboring food source and calculates its fitness value. The bee memorizes the new food source position; if the new source has better fitness value than the previous one, then it forgets the previous one. The food sources with the highest fitness values are visited until it reaches a limited number of cycles. Correspondingly, if the fitness value is not improved during the number of cycles, then a new solution is randomly generated by the scouts

using (4):

$$W_{x,y} = l_y + \text{rand}(0, 1) \times (u_y - l_y) \quad (4)$$

where  $W_{x,y}$  is the abandoned food source and  $l_y \leq W_{x,y} \leq u_y$ .

1) ABC ALGORITHM-BASED NBSs SELECTION MECHANISM  
The proposed ABC algorithm-based NBSs selection mechanism is a centralized control algorithm that ensures the selection of those NBSs for data reporting that will not lead to the sharp depletion of energy resources of IBNNs. The selection procedure is implemented at the NR that is assumed to have more resources than NBSs. The complete demonstration of the selection process is described below:

*a: SOLUTION INITIALIZATION*

ABC algorithm first initializes the initial solution. Each solution represents an array having d items corresponding to the optimal number of NBSs.

*b: FITNESS FUNCTION PARAMETERS*

To determine optimal solutions, a population of bees is employed to fly in the search space with d dimensions. Each employed bee represents an NBS whose fitness is evaluated based on the following parameters:

- *Energy:* Resource constraint NBSs consume maximum energy resources during data communication. Once the energy level of an NBS breaks a critical level, it results in the fast depletion of the network resources. Therefore, energy consumption is a crucial parameter for the calculation of the fitness value. To be selected as an optimal NBS for generating response messages, the energy level of the NBS should be above a threshold level in a given solution. The energy standard for the fitness function is expressed using (5):

$$S = \begin{cases} f(E) \geq \theta & \text{if } C(E) \geq \sigma \\ f(E) \leq \theta & \theta \text{ otherwise} \end{cases} \quad (5)$$

where  $\theta$  and  $\sigma$  are threshold values,  $C(E)$  is the current energy level of  $i^{th}$  NBS, and  $f(E)$  represents the fitness value. The value of  $\theta$  and  $\sigma$  are set to the value of 0.1 and 0.9 to obtain fitness value between 100% and 90% until the battery level reaches a critical level ( $\sigma$ ). The mathematical model of this energy standard is represented (6):

$$\psi = -\phi(C(E)^{ith}) / (T(E)^{ith}) \quad (6)$$

Accordingly, the fitness value can be calculated using (7):

$$f(E) = 1 - e^\psi \quad (7)$$

where  $C(E)$  is the residual energy of the  $i^{th}$  NBS and  $T(E)$  represents the initial energy of the  $i^{th}$  NBS. The parameter  $\phi$  adjust the convexity degree of the fitness

function to obtain the desired value of  $f$  at  $\theta = 10\%$  and  $\sigma = 90\%$ .

- **Link cost function:** Intrabody communication in the THz band is challenged by the high probability of link breakdown due to numerous factors such as low transmission power, path loss, and scattering. Accordingly, when an EM wave is transmitted to travel a larger distance, the path loss is also increased that deteriorates the channel quality. To address these constraints, reducing the distance between the sender and receiver is desirable. Therefore, considering link cost function based on the candidate path (i.e., distance and channel capacity) in evaluating the fitness of an NBS increases the fitness of the NBS, as given in (8):

$$f(LC) = \frac{1}{LC_{NR,NBS}} \quad (8)$$

where the link cost between the NR and candidate NBS can be calculated using (9):

$$Link_{cost} = \lambda f\left(\frac{1}{C_{cap}}\right) + (1 - \lambda)f(D(NR, NBS)) \quad (9)$$

where  $\lambda \in [0, 1]$  represents the cost factor, and  $C_{cap}$  is the channel capacity that can be calculated using (10):

$$C_{cap} = \sum_i \Delta f \log_2\left(1 + \frac{S(f_i)}{PL(f_i, d)N(f_i, d)}\right) \quad (10)$$

where  $\Delta f$ , and  $f_i$  represents the bandwidth and the central frequency of the  $i$ th sub-band. While  $d$  represents the distance between the sender and the receiver, path loss and the noise power are expressed using  $PL(f_i, d)$ , and  $N(f_i, d)$ , respectively.

- **Last interaction interval:** The last interaction interval briefs NR about the most recent data transmission time of the NBS. This selection parameter avoids the selection of those NBSs that have recently transmitted the information and encourages the selection of those NBSs that did not get the chance of data transmission recently. The fitness parameter is calculated using (11):

$$f(LII) = \frac{1}{LII_{NBS \rightarrow NR}} \quad (11)$$

where  $(LII_{NBS \rightarrow NR})$  represents the last interaction interval between the NBS and the NR.

### c: FITNESS VALUE CALCULATION

In the ABC algorithm, the selection of candidate NBS is expressed by a fitness value. The fitness functions derived in the aforementioned equation are unified by assigning weights to each of them to get a single fitness value, given in (12):

$$F(value) = \alpha \times f(E) + \beta \times f(LCF) + \gamma \times f(LII) \quad (12)$$

where the value of  $\alpha + \beta + \gamma = 1$ , and  $f(E)$ ,  $f(LCF)$  and  $f(LII)$  are the fitness parameters for energy, link cost function and last interaction interval, respectively.

---

### Algorithm 2 ABC Algorithm Based-NBSs Selection

---

- 1: **Initialize population**  $nbs = (NBS_1, NBS_2, \dots, NBS_i)T$
  - 2: Perform the generation of initial population,  $(1, 2, \dots, i)$
  - 3: **Repeat**
  - 4: **Employed Bees Phase**
  - 5: **For** each employed bee
  - 6: produce new solutions  $v_i$  according to (2)
  - 7: Calculate the fitness according to (12)
  - 8: Apply the greedy selection process
  - 9: **End For**
  - 10: **Onlooker Bees Phase**
  - 11: **For** each onlooker bee
  - 12: Choose a solution using (3)
  - 13: find new solution using (2)
  - 14: Calculate the fitness according to (12)
  - 15: Apply the greedy selection process
  - 16: **End For**
  - 17: **Scout Bees Phase**
  - 18: **For** each scout bee
  - 19: When solutions can't be improved (reach a limit parameter), then replace it with a new solution produced by a formula given by (4)
  - 20: **End For**
  - 21: Memorize the best solution so far
  - 22: Until Maximum Cycle Number
- 

### 2) TDMA-BASED DATA TRANSMISSION

In IBNNs, communication is carried out using TS-OOK based modulation scheme that transmit data using small pulses with an extremely higher data rate. Therefore, the collision probability is almost negligible [11], [32]. To avoid any slight chance of collision, the selected NBSs transmit data to the NR using the TDMA approach. NRs assign time to each selected NBS in their cluster for data transmission. Later, NRs transmit the aggregated data to the external healthcare system using direct communication or in a multi-hop manner.

### III. ENERGY ANALYSIS OF PROPOSED SCHEME

This section mainly focuses on the energy consumption of our proposed scheme. According to [32], the amount of energy consumed during transmission and reception of data in the TS-OOK based THz channel can be expressed using (13),

and (14):

$$E^{tx}(DP_{Nbits}) = \Omega \times DP_{Nbits} \times E_{ptx} \quad (13)$$

$$E^{rx}(DP_{Nbits}) = DP_{Nbits} \times E_{prx} \quad (14)$$

where the value of  $\Omega$  is set according to the coding weight, which indicate the probability of symbol 1 appearing in the  $Nbit$  of data. The value of  $\omega$  is generally set to 0.5 for equal occurrence probability of symbol 1 and 0 in the stream of  $Nbits$ . Accordingly, the amount of energy consumed ( $E_{exp}$ ) in the whole network for a given period of time  $\tau$  can be expressed using (15):

$$E_{exp}^{\tau} = E_{EWMA-ODT} + E_{ABC-QRT} \quad (15)$$

where  $E_{EWMA-ODT}$  and  $E_{ABC-QRT}$  represents the amount of energy consumed due to EWMA-ODT and ABC-QRT approaches, respectively.

The value of  $E_{ABC-QRT}$  can be calculated using (16):

$$E_{ABC-QRT} = (E^{rx} \times DP_{Nbits}(QM)) + (E^{tx} \times DP_{Nbits}(FBM) + DP_{Nbits}(RM)) \quad (16)$$

where the amount of energy consumed in receiving query messages, transmitting feedback, and response messages are represented as  $DP_{Nbits}(QM)$ ,  $DP_{Nbits}(FBM)$ , and  $DP_{Nbits}(RM)$ , respectively.

Since the energy consumption in the EWMA-ODT is proportional to successful interactions; therefore, the higher the number of successful interaction, the more is the consumed energy as NBSs will transmit more data packets. In order to estimate the energy consumption during the EWMA-ODT approach, the mobility of NBSs and transmission range is incorporated into the energy consumption model of the EWMA-ODT approach through the physical layer duration. We define Physical Layer Interaction (PLI) as the time when a sender (i.e., NBS) is in the transmission range of the receiver (i.e., NR). We assumed that the number of successful interactions is solely based on PLI, and they are independent of the mobility and position of the NBSs. The value of PLI is considered as a random variable that represents the duration of a successful interaction. The mobility of NBSs only provides the input for the probability density function of the PLIs. The event of detecting an NR in the transmission radius of the NBS is expressed as interaction hit, and the probability of interaction hit is denoted by  $P_{IH}$ .  $P_{IH}$  is used for analyzing the average amount of energy consumed in an interaction attempt for establishing a successful interaction. The amount of energy consumed in the successful interaction is denoted by  $E_{SI}$ , obtained as (17):

$$E_{SI} = \frac{1}{T_I \times \lambda_r \times P_{IH}} \quad (17)$$

where  $T_I$  is the interaction interval,  $\lambda_r$  is the number of NBSs that are coming towards NR, and  $P_{IH}$  is the probability of interaction hit. According to Little's theorem, the number

of NBSs in the transmission radius of the NR can be given as (18):

$$N_r = \lambda_r \times E[PLI] \quad (18)$$

where  $E[PLI]$  is the expected value of PLI. Accordingly, the modified  $E_{SI}$  can be given as (19):

$$E_{SI} = \frac{E[PLI]}{T_I \times N_r \times P_{IH}} \quad (19)$$

where  $T_I$  denotes the model parameter, and  $N_r$  denotes the density of NBSs. The remaining section concentrates on the evaluation of  $P_{IH}$  using PLI, probability density function, and cumulative density function, which are denoted as  $I$ ,  $f(I)$ , and  $F(I)$ , respectively. According to the law of total probability, the probability of interaction hit is calculated using (20):

$$P_{IH} = \int_0^{\infty} P_{IH}(I) f_I(I) dI \quad (20)$$

where  $P_{IH}(I)$  is the probability of interaction hit condition on  $I = x$ . For simplicity, the evaluation of  $P_{IH}(x)$  is performed by introducing a random variable  $R$ , which represents the time interval between the arrival of an NBS in the transmission radius of an NR.  $R$  is a uniform random variable in mild conditions when the interactions are generated periodically. Thus for periodic interaction  $P_{IH}(x)$  has the same value as the cdf of  $R$ , denoted by  $F_R(x)$ . The modified equation can be represented as (21):

$$\int_0^{\infty} F_R(I) \times f_I(I) dI \quad (21)$$

Accordingly, the probability of interaction hit for periodic interactions can be estimated using (22):

$$P_{IH} = 1 - \frac{1}{T_I} \int_0^{T_I} F_I(x) dI \quad (22)$$

The pdf  $F_I(d)$  for  $PLI(I)$  for a constant mobility model can be re-written as [33], given in (23):

$$f_t(t) = \frac{4tvR + 2(R-tv)(R+tv) \ln\left(\frac{R+tv}{R-tv}\right)}{\pi^2 R^2 t} \quad (23)$$

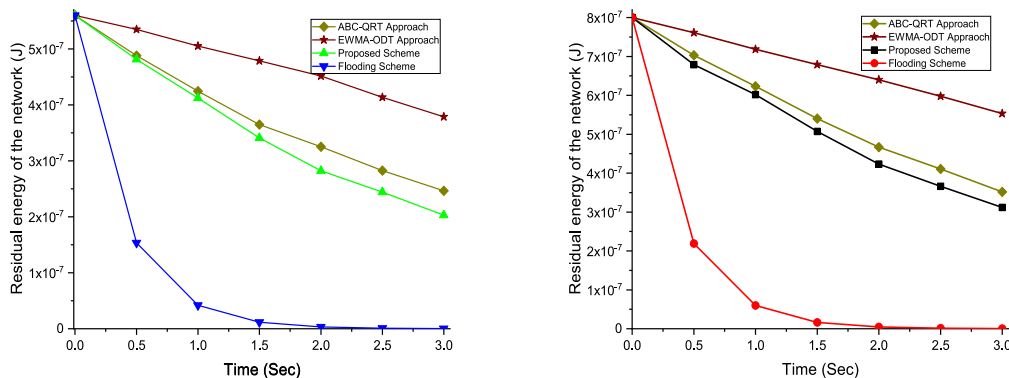
where  $t$  corresponds to the time when an effective link time exists between the NBS and the NR; accordingly, the pdf of PLI can be calculated from the pdf of effective link.

$$f_I(t) = -\frac{df_t(t)}{dt} E[PLI] \quad (24)$$

Finally, the amount of energy consumed in the EWMA-ODT approach  $E(EWMA - ODT)$  is estimated by determining the value of  $E_{SI}$  using (25):

$$E_{SI} = \frac{E[PLI]}{T_I \rho_n \pi R^2 P_{IH}} \quad (25)$$

where  $\rho_n \pi R^2$  is the density of average number of NBSs in the transmission radius of the NR.



(a) Network residual energy comparison with the flooding, EWMA-ODT and ABC-QRT approaches over time with the density of 700 NBSs. (b) Network residual energy comparison with the flooding, EWMA-ODT and ABC-QRT approaches over time with the density of 1000 NBSs.

**FIGURE 3.** Comparison of residual energy of the network with the flooding, EWMA-ODT and ABC-QRT approaches over time with increasing densities of NBSs.

#### IV. SIMULATION AND RESULTS DISCUSSIONS

This section concentrates on the detailed demonstration of simulation parameters and the discussion of obtained results. The extensive simulations are carried out using the Nano-SIM tool to investigate the performance impact of our proposed scheme in comparison with the flooding scheme. In the flooding scheme, NBSs maintains a list of previously sent packets and avoid retransmission of the same packet to the forwarding NBSs that have already transmitted the packet. The existing scheme considered the flooding scheme as the benchmark scheme for evaluating the performance of new EM-based routing schemes [13]. We have also performed a comparison of our proposed scheme with the EWMA-ODT and ABC-QRT approaches to evaluate the individual performance impact of these approaches on the performance of various simulation metrics used for performance evaluation.

##### A. NANO-SIM SIMULATIONS

To perform the simulation, we considered an IBNN expended along the artery of a human arm with a varying number of NBSs (i.e., 700 and 1000) and 5 NRs. The length and diameter of the human arm are considered to be 30 cm and 1 mm, respectively. At the start, NBSs are uniformly distributed over the area of 15 cm of the artery. As time progresses, NBSs maintain a constant movement along the artery, whereas, NRs and nanointerface are assumed to be stationary at fixed positions. The size of the transmitted data packet is set to 176 bits. For the ABC-QRT approach, we have assumed that the external healthcare system is generating queries at varying Query Rate Intervals (QRIs). While the other physical layer settings, including the transmission range of NBSs, and time to live (TTL) are set according to the evaluation parameters of the existing schemes [8], [9], [11], [32]. Table 1 further briefly summarizes the simulation parameters used for performance evaluation.

##### B. PERFORMANCE METRICS

The following metrics are used to evaluate the performance of our proposed routing scheme.

**TABLE 1.** The values of parameters selected for the simulations.

Parameter	Value
Number of NBSs	700, 1000
Number of NR	5
TTL value	100
Tx Range of NBS (mm)	10
Pulse energy (pJ)	100
Pulse duration (fs)	100
Pulse interval time (ps)	10
Packet size ( $P_{RM}$ )	176 (bits)
Simulation duration (s)	3
Total iteration	100

- Residual energy: It shows the average amount of energy left in the network.
- Number of alive NBSs: It corresponds to the NBSs that have residual energy greater than the threshold.
- Average end-to-end delay: It is expressed as the time a packet takes from its transmission to the reception at the NR.
- Average transmission delay: This metric is used for determining the average transmission delay in EWMA-ODT. Average transmission delay is defined as the time interval when an NBS detects an event until its transmission to the NR.
- Packet delivery: It represents the number of packets that are successfully received at the destination.

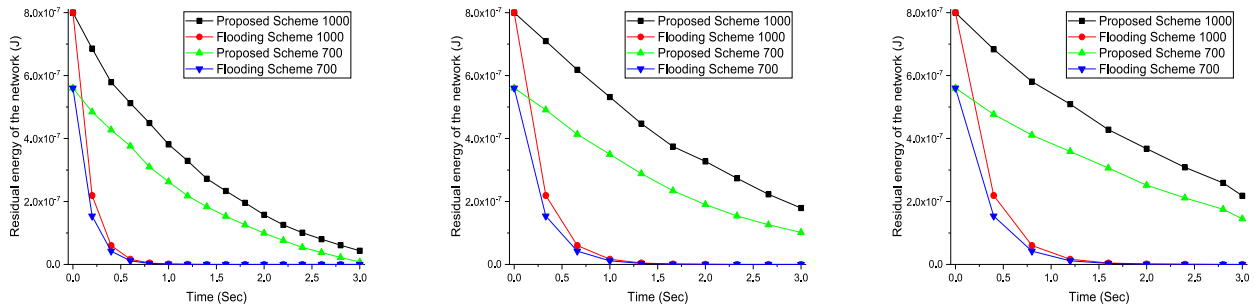
##### C. SIMULATION RESULTS

This section provides a comprehensive discussion of the obtained results to highlight the potential of the proposed scheme for enabling continuous healthcare monitoring.

###### 1) COMPARISON OF RESIDUAL ENERGY OF THE NETWORK OVER TIME WITH THE INCREASING DENSITIES OF NBSs

Fig. 3 represents the residual energy comparison of our proposed scheme with the flooding, EWMA-ODT, and ABC-QRT schemes. Fig. (3a,3b) clearly shows that for both





(a) Network residual energy comparison with flooding scheme over time with the density of 700 NBSs and QRI of 0.2. (b) Network residual energy comparison with flooding scheme over time with the density of 700 NBSs and QRI of 0.3. (c) Network residual energy comparison with flooding scheme over time with the density of 700 NBSs and QRI of 0.4.

**FIGURE 4.** Comparison of residual energy of the network with the flooding scheme over time with increasing QRI and densities of NBSs.

densities of NBS, the EWMA-ODT approach consumes the minimum energy resources of the network due to transmitting data only when a moving NBSs interact with an NR. Thus, when the interaction rate is high more energy is consumed whereas, the ABC-QRT scheme expands more resources as compared to the EWMA-ODT approach as NBS transmit packets when a request message is received. The optimal selection of NBSs also results in maintaining almost similar residual energy resources. Since the energy consumption of our proposed scheme is the combination of EWMA-ODT and ABC-QRT approaches, therefore, our proposed scheme has lower residual energy than EWMA-ODT and ABC-QRT approaches. While flooding scheme experiences the lowest remaining energy as time progresses due to the high packet generation and forwarding rate.

2) COMPARISON OF RESIDUAL ENERGY OF THE NETWORK OVER TIME WITH THE INCREASING DENSITIES OF NBSs AND QRI

Fig. 4 depicts that when the external healthcare system generates queries more frequently, it leads to a sharp depletion of energy resources. Accordingly, Fig. 4a shows that at QRI 0.2, the increased load of generating response message results in higher consumption of energy resources as compared to the energy consumption at QRI of 0.3 and 0.4 (see Fig. (4b,4c)). We can see that at the end of the simulation, due to the maximum QRI rate (i.e., at 0.2 interval), only 10% residual energy is available. In contrast, at the QRI of 0.3 and 0.4, the residual energy of the network is 15% and 20%. The same trend can be observed for the density of 1000 NBSs, where the lowest residual energy is obtained for the QRI of 0.2.

3) RESIDUAL ENERGY OF THE NETWORK COMPARISON WITH THE INCREASING DENSITIES OF NBSs AT THE END OF SIMULATION

The residual energy at the end of the simulation represented in Fig. 7 shows that for both densities of NBSs our proposed scheme outperforms flooding scheme due to the employing EWMA-ODT and ABC-QRT approaches. From Fig. 7, we can see that even under the high response message generation load, our proposed scheme consumes low energy

as compared to the flooding scheme. Moreover, the optimal selection of NBSs also significantly reduces the traffic load due to the increased probability of direct data transmission. Whereas, in the flooding scheme, the high rate of packet generation and packet forwarding increases the traffic load that leads to maximum energy consumption at all query intervals.

4) COMPARISON OF TOTAL NUMBER OF ALIVE NBSs IN THE NETWORK OVER TIME WITH THE INCREASING DENSITIES OF NBSs

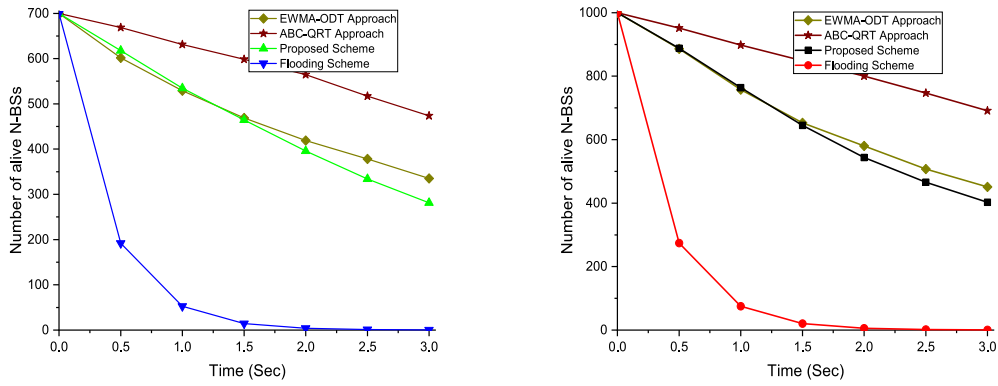
Fig. 5 visually represents the number of alive NBSs with the progression of time. From Fig. (5a, 5b), we can clearly see that EWMA-ODT routing results in the maximum number of alive NBSs for both densities of NBSs (i.e., 700 and 1000). ABC-QRT scheme also maintains a higher number of NBSs that is almost more than 500 and 600 for both NBSs density of 700 and 1000, respectively. Whereas in the flooding scheme, NBSs lose their energy resources more rapidly, resulting in the death of the network.

5) COMPARISON OF TOTAL NUMBER OF ALIVE NBSs IN THE NETWORK OVER TIME WITH THE INCREASING DENSITIES OF NBSs AND QRIs

From Fig.6, it is evident that increasing the query interval rate leads to a low number of alive NBSs. When the query interval is 0.2 for both densities of NBSs, only 20 and 30 NBSs are alive, which is the minimum number of alive NBSs. Whereas, when for the query interval of 0.5, the alive number of NBSs is the maximum for both densities. From Fig.6, we can see that the higher rate of packet generation and packet forwarding rapidly consume the energy resources of NBSs. Therefore, in the flooding scheme, all the NBSs are dead almost at the start of the simulation time.

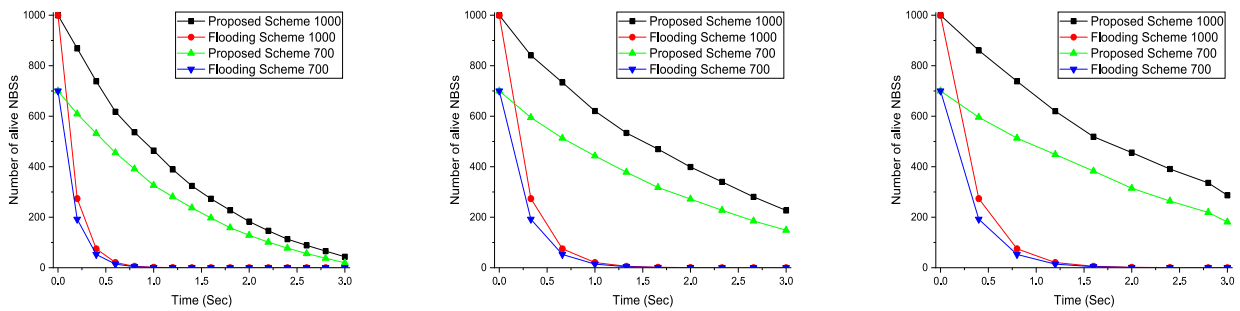
6) COMPARISON OF AVERAGE END-TO-END DELAY WITH THE INCREASING DENSITIES OF NBSs AND QRIs

Fig. 8 represents the average end-to-end delay experienced under different traffic loads. We can observe that at 0.2 QRI, maximum traffic is generated. Therefore the proposed scheme experienced the maximum delay. Whereas, when a low number of packets are generated, the lowest



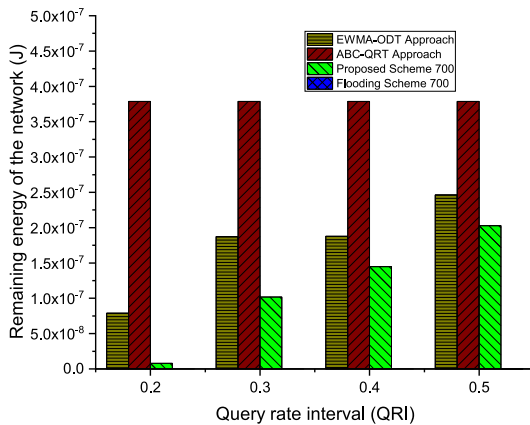
(a) Comparison of total number of alive NBSs with flooding, EWMA-ODT and ABC-QRT approaches over time with the density of 700 NBSs. (b) Comparison of total number of alive NBSs with flooding, EWMA-ODT and ABC-QRT approaches over time with the density of 1000 NBSs.

**FIGURE 5. Comparison of total number of alive NBSs with the flooding, EWMA-ODT and ABC-QRT approaches over time with increasing densities of NBSs.**



(a) Comparison of total number of alive NBSs with flooding scheme over time with the increasing densities of NBSs and QRI of 0.2. (b) Comparison of total number of alive NBSs with flooding scheme over time with the increasing densities of NBSs and QRI of 0.3. (c) Comparison of total number of alive NBSs with flooding scheme over time with the increasing densities of NBSs and QRI of 0.4.

**FIGURE 6. Comparison of residual energy of the network with the flooding scheme over time with increasing QRI and densities of NBSs.**

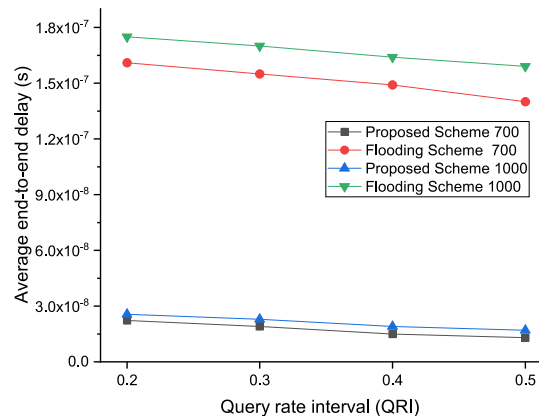


**FIGURE 7. Network residual energy at the end of simulation comparison with flooding scheme with the increasing densities of NBSs.**

average end-to-end delay is observed. Flooding scheme experiences the maximum delay at all query intervals due to the high traffic load caused by increased packet generation and packet forwarding rate.

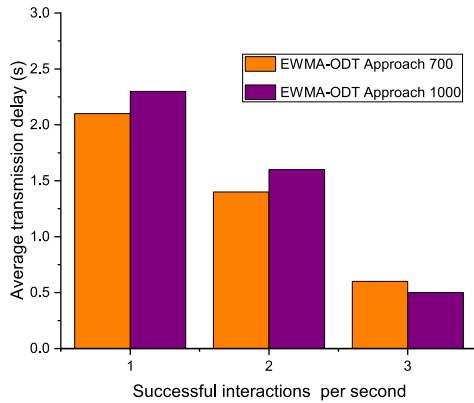
### 7) AVERAGE TRANSMISSION DELAY COMPARISON WITH THE INCREASING DENSITIES OF NBSs

Average transmission delay has a tradeoff with energy consumption as an NBS only transmits data when an NR is

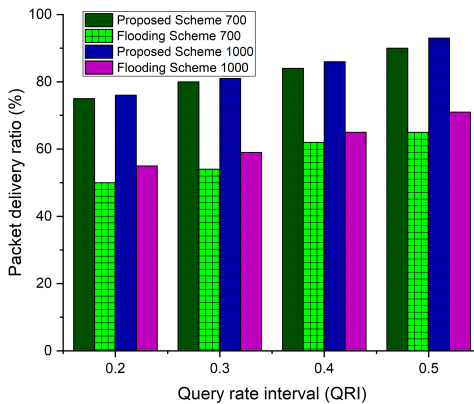


**FIGURE 8. Average end-to-end delay comparison of our proposed scheme with the flooding scheme with the increasing densities of NBSs.**

found in the transmission radius. Thus the experienced delay in increased due to the time gap between event detection and event transmission increases. Fig. 9 clearly shows that for a lower value of average successful interactions, more transmission delay is experienced for both densities of NBSs (i.e., 700 and 1000). Accordingly, when NBS interacts more frequently with NRs, the lowest transmission delay is observed.



**FIGURE 9.** Average transmission delay comparison with the increasing densities of NBSs.



**FIGURE 10.** Packet delivery comparison with the flooding scheme with the increasing densities of NBSs and QRI.

#### 8) PACKET DELIVERY COMPARISON WITH THE INCREASING DENSITIES OF NBSs AND QRIs

The packet delivery of our proposed scheme is visually expressed using Fig. 10 shows under the heavy traffic load (i.e., at QRI 0.2), our proposed scheme experiences the lowest packet delivery. Whereas, the packet delivery increases at the traffic load decreased for both densities of NBSs. Therefore, our proposed achieves more than 90% packet delivery for both densities of NBSs. On the other hand, in the flooding scheme, packet delivery does not exceed 70% due to the high rate of packer generation and forwarding at all QRI.

#### V. CONCLUSION

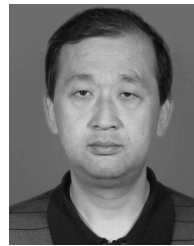
In this work, a novel routing scheme is proposed that integrates EWMA-ODT and ABC-QRT approaches for improving the performance of resource constraint IBNNs. Our proposed EWMA-ODT approach employs EWMA method characteristics for aggregating detected data, which are transmitted to the NR during an occasional direct interaction. The direct transmission of EWMA-based aggregated data assists in notifying the NR about the condition of physiological parameters after their last successful reception with low energy consumption and storage overhead. Whereas, our proposed ABC-QRT approach handles the urgent data retrieval demand of the external healthcare system and ensures the transmission of detected data with

minimum energy consumption and end-to-end delay. ABC algorithm-based NBSs selection mechanism guarantees the selection of those optimal NBSs that have maximum fitness value for reporting data. The optimized selection of NBSs avoids burdening individual NBSs and encourages load balancing among all the NBSs for improving the network lifetime. The extensive comparison and detailed discussion of obtained results validate that our proposed scheme improves 60%-70% network lifetime, 60%-75% alive NBs, and achieves 90% packet delivery with a reduced delay of 25%. From the obtained results, we conclude that our proposed scheme significantly overcome the routing challenges and provides a low complexity routing solution for healthcare monitoring applications.

#### REFERENCES

- [1] I. F. Akyildiz, F. Brunetti, and C. Blázquez, "Nanonetworks: A new communication paradigm," *Comput. Netw.*, vol. 52, no. 12, pp. 2260–2279, Aug. 2008.
- [2] I. F. Akyildiz, J. M. Jornet, and C. Han, "Terahertz band: Next frontier for wireless communications," *Phys. Commun.*, vol. 12, pp. 16–32, Sep. 2014.
- [3] S. Agrawal and R. Prajapati, "Nanosensors and their pharmaceutical applications: A review," *Int. J. Pharmaceutical Sci. Technol.*, vol. 4, no. 4, pp. 1528–1535, Jan./Mar. 2012.
- [4] M. A. Eckert, P. Q. Vu, K. Zhang, D. Kang, M. M. Ali, C. Xu, and W. Zhao, "Novel molecular and nanosensors for *in vivo* sensing," *Theranostics*, vol. 3, no. 8, p. 583, 2013.
- [5] I. F. Akyildiz and J. M. Jornet, "Electromagnetic wireless nanosensor networks," *Nano Commun. Netw.*, vol. 1, no. 1, pp. 3–19, Mar. 2010.
- [6] J. M. Jornet and I. F. Akyildiz, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band," *IEEE Trans. Wireless Commun.*, vol. 10, no. 10, pp. 3211–3221, Oct. 2011.
- [7] S. Sarkar and S. Misra, "From micro to nano: The evolution of wireless sensor-based health care," *IEEE Pulse*, vol. 7, no. 1, pp. 21–25, Jan. 2016.
- [8] F. Afsana, M. Asif-Ur-Rahman, M. R. Ahmed, M. Mahmud, and M. S. Kaiser, "An energy conserving routing scheme for wireless body sensor nanonetwork communication," *IEEE Access*, vol. 6, pp. 9186–9200, 2018.
- [9] H. Fahim, W. Li, S. Javaid, M. M. Sadiq Fareed, G. Ahmed, and M. K. Khattak, "Fuzzy logic and bio-inspired firefly algorithm based routing scheme in intrabody nanonetworks," *Sensors*, vol. 19, no. 24, p. 5526, Dec. 2019.
- [10] H. Fahim, W. Li, S. Javed, and F. Javed, "Bio-inspired nanorouter mobility model for energy efficient data collection in intrabody nanonetwork," in *Proc. Int. Conf. Netw. Netw. Appl. (NaNA)*, Oct. 2019, pp. 124–128.
- [11] G. Piro, G. Boggia, and L. A. Grieco, "On the design of an energy-harvesting protocol stack for body area nano-NETworks," *Nano Commun. Netw.*, vol. 6, no. 2, pp. 74–84, Jun. 2015.
- [12] S. Javaid, Z. Wu, H. Fahim, F. Javed, and J. Chen, "Analyzing the impact of nanonode density on biological tissues in intrabody nanonetworks," in *Proc. Int. Conf. Netw. Netw. Appl. (NaNA)*, Oct. 2018, pp. 159–163.
- [13] G. Piro, L. A. Grieco, G. Boggia, and P. Camarda, "Nano-sim: Simulating electromagnetic-based nanonetworks in the network simulator 3," in *Proc. 6th Int. ICST Conf. Simulation Tools Techn.*, 2013, pp. 203–210.
- [14] S. Canovas-Carrasco, A.-J. Garcia-Sanchez, and J. Garcia-Haro, "A nanoscale communication network scheme and energy model for a human hand scenario," *Nano Commun. Netw.*, vol. 15, pp. 17–27, Mar. 2018.
- [15] P. S. Mann and S. Singh, "Energy-efficient hierarchical routing for wireless sensor networks: A swarm intelligence approach," *Wireless Pers. Commun.*, vol. 92, no. 2, pp. 785–805, Jan. 2017.
- [16] A. A. A. Ari, B. O. Yenke, N. Labraoui, I. Damakoa, and A. Gueroui, "A power efficient cluster-based routing algorithm for wireless sensor networks: Honeybees swarm intelligence based approach," *J. Netw. Comput. Appl.*, vol. 69, pp. 77–97, Jul. 2016.
- [17] H. Fahim, N. Javaid, Z. A. Khan, U. Qasim, S. Javed, A. Hayat, Z. Iqbal, and G. Rehman, "Bio-inspired routing in wireless sensor networks," in *Proc. 9th Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput.*, Jul. 2015, pp. 71–77.

- [18] A. Sarkar and T. S. Murugan, "Cluster head selection for energy efficient and delay-less routing in wireless sensor network," *Wireless Netw.*, vol. 25, no. 1, pp. 303–320, Jan. 2019.
- [19] M. Baskaran and C. Sadagopan, "Synchronous firefly algorithm for cluster head selection in WSN," *Sci. World J.*, vol. 2015, pp. 1–7, Oct. 2015.
- [20] A. Hamzah, M. Shurman, O. Al-Jarrah, and E. Taqieddin, "Energy-efficient fuzzy-logic-based clustering technique for hierarchical routing protocols in wireless sensor networks," *Sensors*, vol. 19, no. 3, p. 561, Jan. 2019.
- [21] E. Tuba, M. Tuba, and M. Beko, "Two stage wireless sensor node localization using firefly algorithm," in *Smart Trends in Systems, Security and Sustainability*. Cham, Switzerland: Springer, 2018, pp. 113–120.
- [22] V.-O. Sai, C.-S. Shieh, T.-T. Nguyen, Y.-C. Lin, M.-F. Horng, and Q.-D. Le, "Parallel firefly algorithm for localization algorithm in wireless sensor network," in *Proc. 3rd Int. Conf. Robot. Vis. Signal Process. (RVSP)*, Nov. 2015, pp. 300–305.
- [23] G. Yogarajan and T. Revathi, "Nature inspired discrete firefly algorithm for optimal mobile data gathering in wireless sensor networks," *Wireless Netw.*, vol. 24, no. 8, pp. 2993–3007, Nov. 2018.
- [24] S. Hamrioui and P. Lorenz, "Bio inspired routing algorithm and efficient communications within IoT," *IEEE Netw.*, vol. 31, no. 5, pp. 74–79, Sep. 2017.
- [25] S. Bitam and A. Mellouk, "Vehicular ad hoc networks," *Bio-Inspired Routing Protocols for Vehicular Ad-Hoc Networks*. Hoboken, NJ, USA: Wiley, 2014, pp. 1–27.
- [26] S. Sukparungsee, Y. Areepong, and R. Taboran, "Exponentially weighted moving average—Moving average charts for monitoring the process mean," *PLoS ONE*, vol. 15, no. 2, 2020, Art. no. e0228208.
- [27] S. Javaid, H. Fahim, Z. Hamid, and F. B. Hussain, "Traffic-aware congestion control (TACC) for wireless multimedia sensor networks," *Multimedia Tools Appl.*, vol. 77, no. 4, pp. 4433–4452, Feb. 2018.
- [28] M. Aslam, G. S. Rao, N. Khan, and F. A. Al-Abbasi, "EWMA control chart using repetitive sampling for monitoring blood glucose levels in type-II diabetes patients," *Symmetry*, vol. 11, no. 1, p. 57, Jan. 2019.
- [29] S. Javaid, Z. Wu, H. Fahim, M. M. S. Fareed, and F. Javed, "Exploiting temporal correlation mechanism for designing temperature-aware energy-efficient routing protocol for intrabody nanonetworks," *IEEE Access*, vol. 8, pp. 75906–75924, 2020.
- [30] S. Javaid, H. Fahim, X. Liao, and F. Javed, "Exploiting temporal correlation mechanism for energy efficient data collection in intrabody nanonetworks," in *Proc. Int. Conf. Netw. Netw. Appl. (NaNA)*, Oct. 2019, pp. 119–123.
- [31] D. Karaboga and B. Akay, "A comparative study of artificial bee colony algorithm," *Appl. Math. Comput.*, vol. 214, no. 1, pp. 108–132, Aug. 2009.
- [32] J. M. Jornet and I. F. Akyildiz, "Femtosecond-long pulse-based modulation for terahertz band communication in nanonetworks," *IEEE Trans. Commun.*, vol. 62, no. 5, pp. 1742–1754, May 2014.
- [33] A. Nayebe, A. Khosravi, and H. Sarbazi-Azad, "On the link excess life in mobile wireless networks," in *Proc. Int. Conf. Computing: Theory Appl. (ICCTA)*, Mar. 2007, pp. 72–76.



**WEI LI** received the bachelor's and master's degrees in computer science from Xi'an Jiaotong University, China, and the Ph.D. degree in systems engineering. He is currently a Professor with Xi'an Jiaotong University. His research interests include computer communications networks, computer network security, network management, wireless networks, network security, anonymous communication, privacy protection, and so on.



**ISMAIL BEN MABROUK** (Senior Member, IEEE) received the B.A.Sc. and M.A.Sc. degrees in electrical engineering from the University of Lille, Lille, France, in 2006 and 2007, respectively, and the Ph.D. degree in electrical engineering from the University of Quebec, Canada, in 2012. From 2007 to 2009, he was with Huawei Technologies, Paris, France. In 2012, he joined the Wireless Devices and Systems (WiDeS) Group, University of Southern California, Los Angeles, CA, USA.

He is currently an Assistant Professor with Al Ain University, Abu Dhabi, United Arab Emirates. His research interests include propagation studies for multiple-input and multiple-output (MIMO) systems, measurement campaigns in special environments, WBAN, and antenna design at the mm-wave and THz frequencies.



**MUATH AL HASAN** (Senior Member, IEEE) received the B.A.Sc. degree in electrical engineering from the Jordan University of Science and Technology, Jordan, in 2005, the M.A.Sc. degree in wireless communications from Yarmouk University, Jordan, in 2008, and the Ph.D. degree in telecommunication engineering from the Institut National de la Recherche Scientifique (INRS), Université du Québec, Canada, in 2015. From 2013 to 2014, he was with Planets Inc., San Francisco, CA, USA. In May 2015, he joined Concordia University, Canada, as a Postdoctoral Fellowship. He is currently an Assistant Professor with Al Ain University, United Arab Emirates. His current research interests include antenna design at mm-wave and terahertz, channel measurements in multiple-input and multiple-output (MIMO) systems, machine learning, and artificial intelligence in antenna design.



**MUHAMMAD BABAR RASHEED** (Member, IEEE) received the master's degree in electrical engineering and the Ph.D. degree in computer engineering from COMSATS University, Islamabad, Pakistan, in 2013 and 2017, respectively. He is currently an Assistant Professor with the Department of Electronics and Electrical Systems, The University of Lahore, Pakistan. He has authored over 27 articles in well reputed journals and conference proceedings and supervised/supervising more than ten students in their final year projects and theses.

His research interests include operations research and optimizations algorithms, machine learning, smart grids, electric vehicles, demand response, and so on. He is an Active Reviewer of many esteemed journals and conferences, including the IEEE TRANSACTIONS, IEEE ACCESS, the IEEE TRANSACTIONS ON INDUSTRY APPLICATION SYSTEMS, *Applied Energy*, *Energies*, and so on.



**HAMZA FAHIM** received the B.S. and M.S. degrees from the Computer Science Department, COMSATS University Islamabad (CUI), Pakistan, in 2012 and 2015, respectively. He is currently pursuing the Ph.D. degree in computer science and networks with the School of Electronics and Information Technology, Xi'an Jiaotong University, China. His current research interests include intrabody nanonetworks, software defined networks, and wireless sensor networks.



**SHUMAILA JAVAID** received the B.S. degree from COMSATS University (CIIT), Pakistan, in 2012, and the M.S. degree in telecommunication and networking from Bahria University, Pakistan, in 2015. She is currently pursuing the Ph.D. degree in computer science with Shaanxi Normal University, China. She is currently a Teaching Associate with the COMSATS Institute of Information Technology (CIIT). Her main research interests include wireless sensor and wireless multimedia sensor

networks, intrabody nanonetworks, underwater acoustic sensor networks, information centric networks, and wireless networking in general.