

FGOR: Flow-Guided Opportunistic Routing for Intra-body Nanonetworks

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Abstract—The advancement of nano-communication has opened the door for the development of intra-body medical application services. Flow-guided nano-communication networks have gained major attraction in recent years as an effective solution for intra-body sensing and actuation. This paper builds a three-layer vertical network structure for intra-body nanonetworks, i.e., nano-nodes, nano-routers and gateway, where data packets generated by nano-nodes are relayed to gateway through nano-routers or other nodes. However, how to guarantee the data transmission through the way of multiple hops in such a scenario is an unsolved challenge. In order to improve the throughput and reduce the energy consumption of intra-body nanonetworks in a single-flow environment where the nano-devices are restricted, a Flow-Guided Opportunistic Routing protocol (FGOR) is proposed. In FGOR, a Relative Position (RP) model is proposed to formulate the criterion for Candidate Relay Selection (CRS) and enable the nodes direction-awareness to gateway. Moreover, the CRS criterion is redesigned through a Mobility Gradient (MG) model further derived from the RP model. The candidate nodes are prioritized based on node ID, available energy and relative position information of nodes to perform back-off forwarding for decreasing transmission redundancy. Simulation results show that the RP model improves the throughput and significantly extends the lifecycle of intra-body nanonetwork by reducing the energy consumption. Compared with the RP model, the MG model performs better in terms of delay and successful transmission rate, especially within circulation environment of intra-body.

Index Terms—Intra-body Nanonetworks, Opportunistic Routing, Candidate Relay Selection, Relative Position Model, Mobility Gradient Model.

I. INTRODUCTION

RECENTLY, the development of nanotechnology has provided a new path for disease diagnosis and treatment, and laid the foundation for new medical applications [1]. This technology makes it possible to deploy small-sized devices in the human body [2], [3]. For example, each nano-node can be equipped with nano-sensors, which can provide a better diagnostic experience for patients [4], [5]. By means of biodegradable devices or disposable devices, a swarm of nano-nodes can be distributed in various parts of human body (such as blood vessels) to satisfy specific requirements [6], [7], [8]. Without loss of generality, in this paper, a nanonetwork composed of multiple nano-nodes in the circulatory system

of the human body is called a flow-guided intra-body nano-communication network.

In this kind of network, there are three major challenges: First, due to the miniaturization of the antenna in a nano-node, high-frequency communication is required [9]. As shown in Table I, in the high frequency range, there are a few differences in the transmission range of mm-Wave, Sub-THz and THz. Meanwhile, compared with mm-Wave and Sub THz, THz owns excellent data rate and uses less energy per bit. The attenuation of electromagnetic signal in THz band is very large, especially in the human body [14], [15], [16], [17]. Consequently, high path loss (including spreading loss and absorption loss) limits the communication range of nano-nodes [18], [19], [20]. Correspondingly, nano-routers and gateway communicating with nano-nodes in the same THz frequency are also affected. Second, owing to the constricted communication coverage of nano-routers or gateway in blood vessels, it is worth considering how to utilize the unidirectional movement of blood-driven nano-nodes to transmit the sensing information to the macro device (wearable device or smartphone). Through a hierarchical structure based on the function of devices, higher efficiency and wider coverage can be achieved. Finally, intra-body terahertz communication with high loss results in higher communication energy consumption and nano-batteries cannot be manually replaced or charged, which requires us to design more efficient communication protocols. Moreover, the blood components (platelets, red blood cells, white blood cells, among others) will seize part of the energy. As a result, the absorbed power will activate the vibration of the particles and cause heat generation and temperature increase in the blood components [21].

In order to overcome the above challenges, one possible solution is a three-layer network structure, which was first proposed in [1], [22]. It follows a vertical distribution structure and consists of three different devices [23], [24], [25], [26]. The bottom layer is composed of nano-nodes with limited calculation and storage resources, which are responsible for sensing and generating native data in the network. The middle layer consists of nano-routers that have fewer resource restrictions. Nano-routers are responsible for collecting data from the nano-nodes and forwarding it to the upper layer, such as gateways. This topology has two main advantages [23], [27]: (i) By shifting heavy computing tasks to the devices with larger and richer computing resources, the energy consumption of nano-nodes in the network is reduced. (ii) Through multi-hop transmission at different layers, the single hop distance of packet transmission from nano-nodes to the gateway is minimized while alleviating high path loss [28].

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TABLE I: Characteristics of Related Frequency Bands

| Frequency range | Antenna use | Transmission range | Data rate | Energy per bit |
|-----------------|--------------------------------|--------------------|-----------|----------------|
| UWB [10], [11] | meander type dipole | 1 mm | 1.16 Gbps | 25.86 pJ |
| mm-Wave[12] | zigzag antenna | 20 mm | 16 Gbps | 2.3 pJ |
| Sub-THz[13] | planar microstrip antenna | 10 – 20 mm | 320 Gbps | 4.5 pJ |
| THz[13] | carbon nanotube (CNT) antennas | 23 mm | 240 Gbps | 0.33 pJ |

By considering this network topology, an appropriate solution for flow-guided networks is provided by implanting nano-routers along the flow direction to achieve and guarantee interconnection between nano-nodes and gateways.

In addition, the mobility of nano-nodes causes many issues [29], such as the increase of packet loss rate, the change of terahertz channel quality and dynamic network topology due to real-time movement. Although the mobility of the nodes causes dynamic changes in their communication links with other nodes, it also increases the communication opportunities. Therefore, this paper adopts opportunistic routing proposed by some scholars in wireless sensor networks [30]. Opportunistic routing makes full use of the characteristics of wireless broadcasting to transfer data packets to multiple candidate nodes. The candidate nodes with the highest priority perform packet forwarding. This process consists of candidate node selection and candidate node forwarding. In [31], Juan Xu et al. have conducted some work on opportunistic routing in the field of nanonetworks when all nano-nodes are within the communication range of the gateway. Nevertheless, for mobile applications, it is inevitable for nodes to move beyond the communication range of the gateway. Concurrently, the limited deployment of nano-routers in blood vessel application scenarios [32] and the limited storage of nano-nodes require that the routing protocol is designed to transmit data packets as soon as possible, otherwise there is an increased risk of packet loss and omissions in disease detection [33].

The main contributions of this paper are given as follows:

a) Flow-guided mechanism based on index value: For the three-layer network structure, a mechanism is designed to update the index value of the nano-nodes and confirm the flow direction based on the index value. In this mechanism, index value of the gateway increases periodically, and the gateway informs the nano-nodes within the communication range to update their index. Based on the opportunity routing, the index value is added as a way to achieve communication between the nano-nodes and the gateway and improve the data transmission rate.

b) Relative Position (RP) model: This model is introduced to solve the problem of convergence performance (forwarding to gateway), based on the relative position originating from the blood flow and the mobility of nodes. Combined with flow guidance in the blood vessel, the index of nodes decreases along the direction of blood flow. Index reflects the relative position between nano-node and gateway, since nodes with greater index are theoretically closer to the gateway. Furthermore, related Candidate Relay Selection criterion (CRS) could be established based on the relative position information.

c) Mobility Gradient (MG) model: Due to the dynamic environment of human body, the relative position represented

by index in the RP model may not match well with the actual situation. Nodes with higher index may move faster than nodes with lower index, causing deviation during data packet routing. For more precise mapping of nano-nodes' current location, we developed the MG model derived from the RP model. The nano-nodes in the network are divided into several gradients, the local mobility of nodes can be obtained by calculating the average of the indexes of nodes within one gradient. The mobility gradient redesigns the CRS criterion and makes the packet routing more accurate.

d) Back-off forwarding mechanism: Back-off forwarding is combined with the above two models in this paper to reduce transmission redundancy by utilizing the index value. Forwarding priority of nano-nodes is defined as the function of index and the back-off time is an inverse proportional function of priority. Back-off time determines how much time the node is supposed to wait before forwarding. Nodes with higher index have higher priority and less back-off time. Based on back-off forwarding mechanism, packet forwarding in the network is better organized.

The rest of the paper is organized as follows: In Sec. II, we present the existing related studies in nanonetworks. In Sec. III, we propose the FGOR protocol, including two models, related CRS criteria and a candidate node forwarding mechanism. In Sec. IV, we provide performance evaluation for the proposed protocol under different conditions, and the security of nano-nodes implanted in the human body is verified. Finally, in Sec. V we discuss the conclusions and future directions.

II. RELATED WORKS

A. Traditional Routing Protocols in Nanonetworks

The challenges associated with routing in nanonetworks were first analyzed in [22]. In [34], a new random routing algorithm was designed and the selective flooding routing scheme was proposed to prevent the waste of bandwidth. Considering saving energy for nano-nodes, a routing framework for Wireless Nano Sensor Networks (WNSNs) was proposed to optimize the utilization of harvested energy in [25]. [35] proposed an energy efficient data collection mechanism in which the nodes of the network are in two states. However, the packet loss is high when some nodes are in a sleeping state. [36] proposed a routing algorithm based on the distance between node and gateway, but this leads to an exponential increase of duplicated packets and causes the waste of network resources. Considering the limited energy of nano-nodes, an energy-efficient routing scheme was proposed in [23]. However, ordinary nodes forward and receive data packets blindly may cause congestion in this scheme. Xu

et al. [24] proposed an Energy Balance Clustering Routing protocol (EBCR) for vivo nano-nodes with low computing and processing power. However, it is assumed that the routing protocol is designed under the premise that both nano-nodes and cluster nodes are static, which is unsuitable for real mobile nanonetworks applications. [37] proposed an energy-efficient cooperative routing algorithm with optimal link cost, which based on a cooperative communication model for hierarchical cluster-based nanonetworks. However, this routing algorithm was unsuitable for flow-guided intra-body environment.

In [23], [34], some protocols have been proposed to improve the transmission efficiency of data packets in nanonetworks. These research achievements mainly emphasized on the problems of energy consumption, packet loss or packet forwarding [26], [25], [35], [36]. Recently, some works tried to propose more comprehensive protocols to solve the above problems, but their potential application scenarios cannot be used in intra-body mobile nanonetworks. [38] analyzed the characteristics of intra-body nanonetworks and defined the requirements for their applicability to the routing algorithm. Therefore, how to design a routing protocol that organizes nano-nodes to transmit data packets reliably and energy-efficiently in mobile nanonetworks is the key to the application of wireless nano-sensor networks in the human body.

B. Location-aware Routing Protocols in Mobility Environment

Because of the high mobility of nano-nodes, intra-body nanonetworks frequently use dynamic topology. This network dynamicity adds a level of complexity to routing strategies that should be taken into consideration when designing routing protocols [39]. In general, reactive routing is better for mobile network with high mobility and dynamic topology. The reactive routing protocols tend to reduce the routing overhead and lower energy consumption at the cost of increased delay in finding new routes. In [40], the energy consumption of the mobile nodes is reduced by limiting the area of discovering range for new available nodes. And this paper also shows the benefits of using location information to improve network performance. But unlike macroscopic devices, the position of nano-nodes cannot be located by Global Positioning Systems (GPS). Rather than using geographical location information provided by positioning devices, we have to build a routing protocol with the ability of location-awareness.

There are some location-aware or mobility-aware routing protocols proposed for multi-hop wireless networks of high velocity mobile nodes. In [31], a node motion vector model is introduced to reflect the mobility of nodes. But this motion vector is calculated by the distance between the nano-node and the control node, which is not easy to be measured in intra-body nanonetworks. [41] proposed a fuzzy logic-based mobility management (FLMM), which uses the distance from nano-controller to nano-nodes as local parameters. But this distance is calculated on assumption of nano-nodes linearly moving in random directions with a constant velocity. And this FLMM is not appropriate for intra-body nanonetworks. Some researchers tend to locate nano-nodes based on node trilateration in [42]. It defines a geometric volume within the

network space that contains the communicating node pair. But we can hardly build one in blood vessels with irregular shapes. The problem is to design a strategy that can reflect the velocity of moving nano-nodes with low cost in a suitable way. Above-mentioned researches have difficulties in locating nano-nodes in blood flows.

C. Energy Harvesting in the Human Body

In nanonetworks, the energy of nano-node is very limited. Besides designing an energy-efficient routing protocol, the energy harvesting of nano-nodes also should be considered [43]. Nano-nodes can power their circuits through energy harvesting technology based on piezoelectric nano-generators. From the energy analysis of nanonetworks in [44], the expression of the energy collected by the piezoelectric nano-generators can be derived, which is about the function of time (t) and the maximum storable energy of the nano-node capacitor Q_{MAX} [45]:

$$q(t) = (Q_{MAX}) \cdot \left(1 - e^{-\frac{-t\Delta c f v_g}{2Q_{MAX}}}\right)^2, \quad (1)$$

where Δc is the electric charge (calculated in coulombs) generated during the compression release cycle of the piezoelectric nano-generator, v_g refers to the voltage induced by the nano-generator during the compression release cycle, and f is the frequency of the compression release cycle. According to the values used in [43], [44], for the 500 um^2 nanometer generator, we set Δc and v_g to 3 pC and 0.2 V , respectively. As the nano-nodes flow through the bloodstream, the frequency of the compression release cycle matches the heart rate, which is about 1 cycle per second (1 Hz). From the equation, the variable t is separated to obtain the time required for the energy harvesting quantity q :

$$t(q) = -\frac{2 \cdot Q_{MAX}}{v_g \cdot \Delta c \cdot f} \cdot \ln \left(1 - \sqrt{\frac{q}{Q_{MAX}}}\right). \quad (2)$$

The expression $\lambda_h(t)$ of the energy harvesting rate with respect to time t can be obtained from the time partial derivative of $q(t)$:

$$\lambda_h(t) = \frac{\partial q(t)}{\partial t} = v_g \cdot \Delta c \cdot f \cdot \left(1 - e^{-\frac{-t\Delta c f v_g}{2Q_{MAX}}}\right) \cdot e^{-\frac{-t\Delta c f v_g}{2Q_{MAX}}}. \quad (3)$$

Finally, by substituting the formula, the energy collection rate (J/s) can be calculated as a function of actual energy:

$$\lambda_h(q) = \Delta c \cdot f \cdot v_g \cdot \sqrt{\frac{q}{Q_{MAX}}} \cdot \left(1 - \sqrt{\frac{q}{Q_{MAX}}}\right). \quad (4)$$

After a time slot of T seconds, the energy harvested by the node (q_h) can be finally expressed as the production of the harvest rate $\lambda_h(q)$ and the duration of the time slot T :

$$q_h(q) = \lambda_h(q) \cdot T. \quad (5)$$

D. The Effect of Temperature Rising Caused by Nano-nodes

Although the study of nanonetworks within the human body is still at its infancy, some researchers concerning the safety of nano-nodes have been considered. The temperature nearby

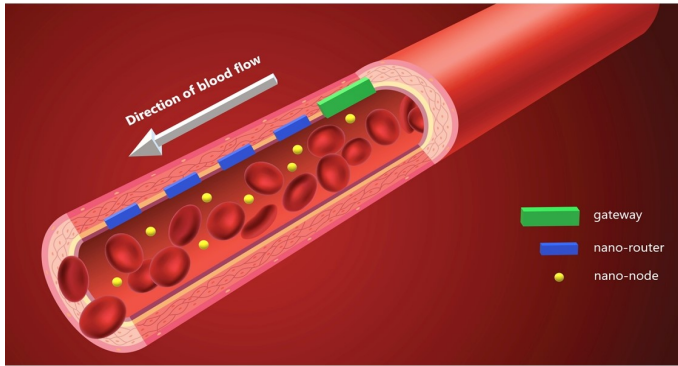


Fig. 1. Whole Picture of Network

the implantable nano-nodes will rise by the effect of energy released from nodes during communication. Therefore, the range of temperature increase should be calculated to ensure the safety of cells or other parts in the human body. The modeling of communication channel noise at THz band was conducted in [46], [47]. A basic physical mechanism behind the molecular absorption noise was introduced in [48]. Further research in [49], the photo-thermal effect on red blood cells induced by electromagnetic waves of communications between nodes can be simulated through stochastic geometry. [21] presented a novel thermal noise model allowing the quantization of the temperature increase resulting from THz frequency absorption. The model uses a mathematical framework based on the heat diffusion model to characterize how molecules in the human body absorb energy from electromagnetic nanoscale communication. [50] evaluated the effect of molecular absorption of the channel model and highlighted the health issues corresponding to the communications in the THz band. Therefore, the heat effect on cells caused by the loss of energy in communication should be analyzed and calculated quantitatively. Simulations have proven that the surrounding temperature increase caused by heat energy is still in a safe range [50].

III. DESIGN OF FGOR PROTOCOL

Without loss of generality, in this paper, a blood vessel is selected as one example of intra-body nanonetworks, as shown in Fig. 1. In detail, the gateway is the fixed final information destination, nano-routers are deployed along the blood vessel, and mobile nano-nodes are used to detect and monitor different biomarkers. In this three-layer vertical network structure, nano-nodes as human body monitors are responsible for collecting critical health-related information. Information collected by the nano-nodes is packaged into data packets and transmitted to the gateway, which is not difficult for the nano-nodes that can reach the gateway directly during their communication range. But for the nodes outside of communication range, their data packets could not be delivered to the gateway directly, so there are two possible ways for

data transmission: in one case, if there are available nano-routers, data packets will be transmitted to the nano-routers and relayed to the gateway. In the other case, if all nano-routers are unreachable directly, data packets will be first sent to neighboring nano-nodes, then forwarded to other nearby nano-nodes, and finally arrive at nano-routers or gateway. Thanks to the stability of nano-routers deployed along the blood vessel, the forwarding routes of data packets are steady in the first case. While in the second case, the dynamic moving of nano-nodes will lead to unstable routing. Therefore, an appropriate routing protocol is required to deal with the instability and further improve the transmission efficiency, which is presented as Flow-Guided Opportunistic Routing Protocol (FGOR) in this section.

A. FGOR Protocol

In this three-layer structure nanonetwork, the gateway plays a critical role. Probe packets are periodically spread out by gateway and received by the nano-nodes through communications. The index of gateway used in the probe packet header is periodically increased from 0 and the initial value of Time To Live (TTL) is set to 1. The nano-nodes within one hop communication range update their indexes stored in their memories according to the probe packets, other nano-nodes outside the communication range keep their indexes, so the nano-nodes closer to the gateway always have higher index value. The maximum value of the index is 128, and the gateway will reset its index to 0 when the index increases to its maximum value.

The detailed flowchart of forwarding strategy in FGOR protocol is shown as Fig. 2. Nano-source periodically sends probe packets like the gateway to find the available neighbors. The main difference between these two kinds of probe packets is whether the source node ID is 0. In the simulation, the ID number of each node in the network is in order from 1 to n (suppose there are n nodes in total, the ID of the gateway is 0 by default). The header of the data packet is shown as Fig. 3. For neighboring nano-node, if it received a probe packet where the value of Source node ID is equal to 0, it updates its index value. If not, it compares its own index value with the index value of the received probe packet and sends back a reply packet (the header of the reply packet is shown in Fig. 4). The source node updates the *tag.type* in the data packet according to the NodeId in the successfully received reply packet. If there is a nano-router in neighbors, the *tag.type* of data packet is set to 1, and if there is a gateway in neighbors, the *tag.type* is set to 0. If not, a certain group of neighbors is chosen as the relay candidates according to a particular criterion, i.e., CRS will be presented in the following subsections, and the *tag.type* of data packet is set to 1. It should be noted that the value of *tag.type* represents the type of the next nano-device for further forwarding. Nano-source sends out the real data packet after setting *tag.type*. Then neighbors receive the data packet from nano-source, and decide to store or discard the data packet according to the *tag.type* of the received data packet. If *tag.type* equals to 1, nano-router keeps the packet and forwards it to adjacent nano-routers in multi

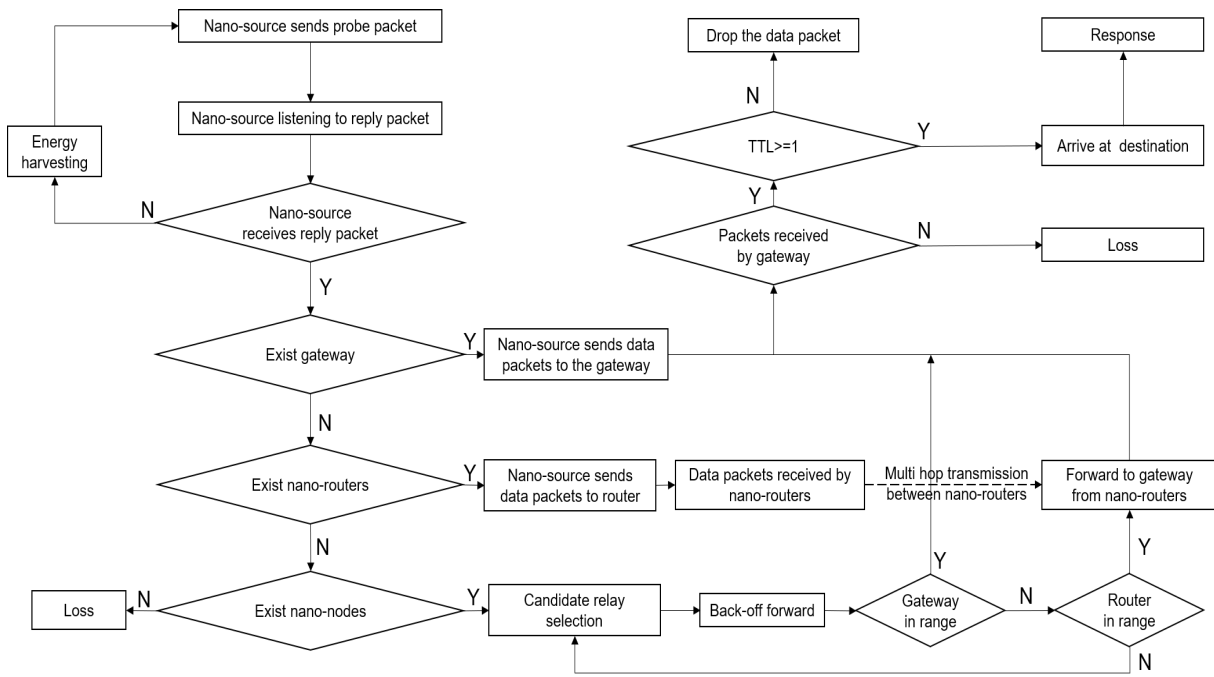


Fig. 2. Flowchart of FGOR Protocol

| Source | Destination | TTL | PacketId | Index | NodeId | Tag |
|--------|-------------|-----|----------|-------|--------|-----|
|--------|-------------|-----|----------|-------|--------|-----|

Fig. 3. Header Format of Data Packet with RP Model

| Source | Destination | TTL | PacketId | Index | NodeId | NodeEnergy |
|--------|-------------|-----|----------|-------|--------|------------|
|--------|-------------|-----|----------|-------|--------|------------|

Fig. 4. Header Format of Reply Packet with RP Model

hop transmission. Other neighbors discard the data packet. If *tag.type* equals to 2, nano-node will conduct the back-off forwarding mechanism. This process will be repeated until the packet is finally received by the gateway.

Furthermore, the CRS is the key factor to improve the efficiency of the proposed FGOR protocol. Since the mobility of nano-node is quite random and intricate, the CRS must be based on the real situation of the mobile nano-nodes. Therefore, in the following subsections, two CRS models (i.e., RP model and MG model) for mobile intra-body nanonetworks are proposed to effectively establish the related CRS.

B. Relative Position (RP) Model

In mobile nanonetworks, the mobility of nano-nodes has great impact on the performance of nanonetworks. Nevertheless, the deployment of traditional position sensors (such as GPS) is impossible in nano-scaled applications due to the very limited size of nano-nodes, which makes mobile nano-nodes blind in the awareness of position and movement. When selecting a forwarding nano-node, it is impossible to determine the geographic location of the source node and gateway. So in this paper, the relative position between mobile nodes and stationary gateway is firstly considered by sending signals to inform the nodes in the communication range. The nano-nodes

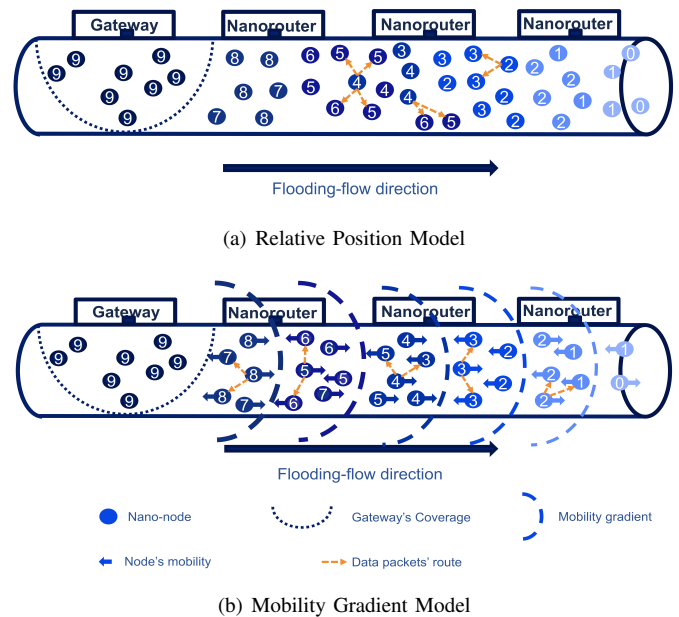


Fig. 5. Relative Position Model and Mobility Gradient Model

flowing through the gateway will receive the updated signals successively in the blood with unidirectional fluidity. After a period of time, the value of signal can be used to represent the distance between the nano-node and gateway. It means that nano-node with a newer signal is closer to the gateway. The continuous updating of the signal sent by the gateway and the mobility of the flow guidance make the Relative Position (RP) meaningful. Based on this idea, an RP model of nano-nodes in mobile nanonetworks based on flow guidance is designed.

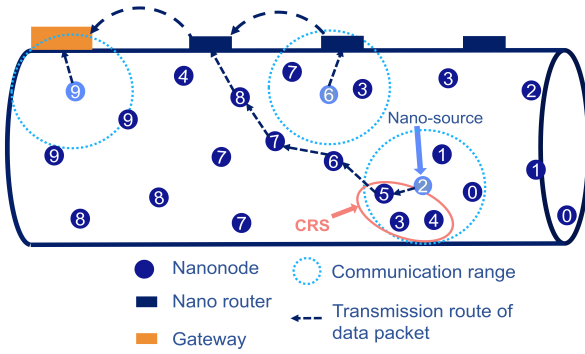


Fig. 6. CRS of the RP model

As shown in Fig. 5, the blood vessel in the human body is modeled as a cylinder nanonetwork, the solid circles represent the nano-nodes, and the solid squares represent the nano-routers and gateway (sink node) deployed on the vessel wall. The sink node sends out the probe packet periodically with updating index in the header of the packet. The nano-node updates its index once receiving the probe packet continuously. The node does not change the index value before receiving the probe packet, and its initial value of index is 0. As can be seen from Fig. 5, the index of nano-nodes decreases along the flow direction. In addition, TTL reflects the forwarding time of a packet and tally down to 0. Packet will be discarded when TTL turns to 0. So TTL of probe packet is set to 1 to prevent nano-nodes from forwarding the probe packet.

Correspondingly, the CRS criterion of RP model on the side of nano-nodes is determined as follows. Nano-source node sends probe packets to neighbors periodically and gets responses from them. Nano-source compares its index value with replier's index values and then transfers data packets to the selected neighbors. In RP model, nano-nodes with newer (greater) values are always closer to gateway, so the data packets should be transmitted to them with high priority. The process of CRS with RP model is shown in Fig. 6. In detail, surrounding nano-nodes whose indexes are greater than nano-source would be selected as candidates.

C. Mobility Gradient (MG) Model

The relative position presented in the above RP model is the main metric for the selection of relay candidates, while it may have some problems in some cases. As shown in Fig. 5(a), nano-source transmits data packets to the neighbors with higher index according to the CRS criterion, but their relative position to the gateway is much farther than source node. The reason is that the moving direction of nano-nodes is ignored in the RP model, which should be further considered as another main factor in the process of candidates selection. So in this subsection, a more comprehensive and precise model (i.e., MG model) is designed and proposed based on the above RP model.

As shown in Fig. 5(b), the index value of nano-node decreases from the gateway along the direction of the flooding-flow, which can be regarded as a declining gradient. Moreover, nano-node can periodically obtain gradient information during

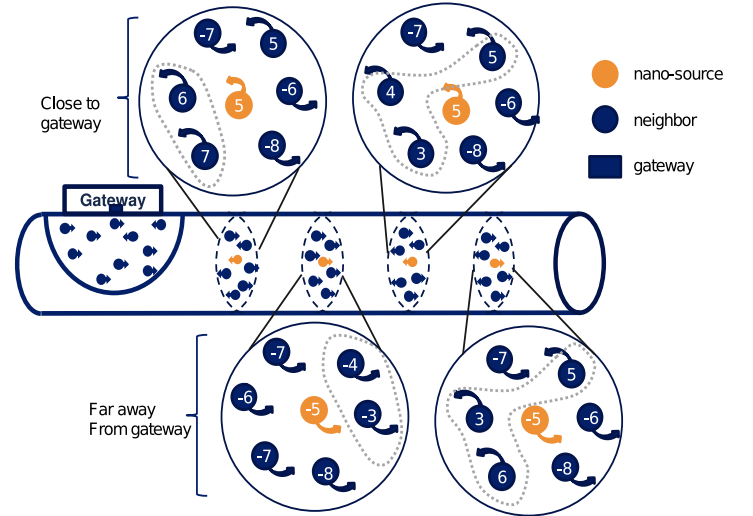


Fig. 7. CRS of the MG model

the movement, the direction of movement relative to the gateway can be regarded as another criterion of CRS. In one cycle, nano-source obtains the index of surrounding nano-nodes, and calculates the average index \overline{Index} . According to the change of gradient information in one cycle, nano-node can calculate its own relative mobility gradient as follows:

$$\partial \overline{Index} = \frac{\Delta \overline{Index}}{\Delta t}, \quad (6)$$

where $\Delta \overline{Index}$ is the difference between the value in the previous cycle and the value in the current cycle, Δt is the duration of two cycles, and $\partial \overline{Index}$ represents the mobility direction of nano-node. This new CRS criterion is based on the relative mobility direction between the source node and the surrounding nodes, which will effectively improve the transmission efficiency of the routing protocol for intra-body mobile nanonetworks.

The CRS process of the MG model is shown in Fig. 7. The number on each nano-node represents its own moving speed (including direction) in the latest cycle. The arrows on the nano-nodes represent their moving directions. In order to increase the probability of successful transmission, the actions of nano-source nodes in two cases and four situations are presented as follows: i) When nano-source node is approaching the gateway, neighbors moving faster than nano-source toward the gateway are selected as relay candidates. If there is no neighbor moving toward gateway faster than nano-source, neighbors moving toward gateway are selected as relay candidates. If there is no neighbor moving toward the gateway, the relay candidate set is empty. ii) When nano-source is moving away from gateway, neighbors moving toward gateway are selected as relay candidates. If there is no neighbor moving toward gateway, neighbors moving away from gateway slower than nano-source are selected as relay candidates. If there is no neighbor moving away from gateway slower than nano-source, the relay candidate set is empty. Noted that the header formats of different packets with MG model are different as shown in Fig. 8 and Fig. 9. Moreover, the corresponding pseudo code is

| Source | Destination | TTL | PacketId | $\overline{\partial Index}$ | NodeId | Tag |
|--------|-------------|-----|----------|-----------------------------|--------|-----|
|--------|-------------|-----|----------|-----------------------------|--------|-----|

Fig. 8. Header Format of Data Packet with MG Model

| Source | Destination | TTL | PacketId | $\overline{\partial Index}$ | NodeId | NodeEnergy |
|--------|-------------|-----|----------|-----------------------------|--------|------------|
|--------|-------------|-----|----------|-----------------------------|--------|------------|

Fig. 9. Header Format of Reply Packet with MG Model

shown in Fig. 10. In detail, S refers to source node carrying data packet, and V refers to nano-nodes. S finds neighbour nodes marked N_i and sends probe packets to N_i . From the reply packet provided by N_i , S will execute different options according to NodeId value in reply packet. The *tag.type* is also updated in header of data packet.

D. Candidate Node Back-off Forwarding Mechanism in Mobile Nanonetwork

As nano-nodes with high density coexist in intra-body nanonetworks, congestion is very likely to happen if nodes are not well organized for spreading and forwarding. One possible solution is to define the forwarding priority of candidate nodes, then candidates will conduct back-off forwarding according to the priority after receiving data. Specifically, when the candidate nodes with different priorities start the back-off forwarding, the node having the highest priority starts forwarding packets first. If the forwarding is successful, it will inform the remaining candidate nodes to discard the current packet by ACK packet. If one of the remaining nodes is not informed within their back-off time, it will consider itself as the first candidate and complete the forwarding process. In this process, the priority is related to the time slot allocation of the candidates. The priority determines the time slot allocation of the candidates. The back-off time T_{b-o} of the candidate v_i in the set is related to the energy-harvesting rate, residual energy, \overline{Index} and $\overline{\partial Index}$ of the node according to the MG model. The back-off time T_{b-o} follows an exponential distribution, whose probability density function [31] can be expressed:

$$f_{T_{b-o}}(t) = \frac{1}{\lambda(v_i)} e^{-\frac{t}{\lambda(v_i)}}, \quad (7)$$

where $\lambda(v_i)$ is the average back-off time of v_i , which is the function of selection metric:

$$\lambda(v_i) = K_{b-o}/M_{v_i}, \quad (8)$$

where K_{b-o} refers to system constant. For RP model, M_{v_i} represents the forwarding priority of nano-node v_i , which can be calculated:

$$M_{v_i} = \lambda_1 RE + \lambda_2 \overline{Index}_n. \quad (9)$$

For MG model, the forwarding priority M_{v_i} of nano-node v_i can be calculated:

$$M_{v_i} = \lambda_1 RE + \lambda_2 \overline{\partial Index} + \lambda_3 \overline{Index}, \quad (10)$$

where $\lambda_1, \lambda_2, \lambda_3$ are all system parameters. RE is the survival model of candidates:

$$RE = \frac{r_{eh} \log \mu}{E_{\max} (\mu^\lambda - 1)}, \lambda = \frac{E_{\max} - E_{re}}{E_{\max}}, \quad (11)$$

Start

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for each node  $i$  in  $V$ 
  nano-node  $V_i$  generates a packet
  nano-node  $V_i$  becomes source node  $S$ 
  if  $S$  has neighbour node  $N_i$ 
     $S.CRS \leftarrow N_i$ 
    if  $N_i.id == gateway.id$ :
       $N_i$  is a gateway
      packet.tag.type = 0
       $S$  sends packet to gateway
    else if  $N_i.id == router.id$ :
       $N_i$  is a router node
      packet.tag.type = 1
       $S$  sends packet to router node
      router node sends packet to gateway
    else if  $N_i.id == node.id$ :
       $N_i$  is a nano node
      packet.tag.type = 2
       $S$  sends packet to nano node
       $S$  selects candidate nodes again
    else
       $S$  capture energy
  else
     $S$  capture energy
End

```

Fig. 10. The CRS strategy

where μ is the system parameter and E_{\max} is the maximum energy. According to the prototype design and corresponding circuit model of the piezoelectric nano-generator, the harvested energy is stored in the nano capacitor of nano-nodes and E_{\max} can be calculated as a function of the total capacitance C_{cap} and generator voltage V_g :

$$E_{max} = \max \left\{ \frac{1}{2} Cap (V_{cap}(n_{cyc}))^2 \right\} = \frac{1}{2} C_{cap} V_g^2. \quad (12)$$

The energy-harvesting rate r_{eh} of nano-node is calculated in the unit of Joule per second as follows:

$$r_{eh}(E_{re}, \Delta E) = \left(\frac{n_{cyc}}{t_{cyc}} \right) \frac{\Delta E}{n_{cyc}(E_{re} + \Delta E) - n_{cyc}(E_{re})}, \quad (13)$$

where ΔE is the energy increment of the capacitor, t_{cyc} is the cycle time, n_{cyc} is the number of cycles required to charge the nano capacitor to E_{re} .

IV. SIMULATION ANALYSIS

In this section, in order to evaluate the performance of FGOR for intra-body mobile nanonetworks and the biosecurity of intra-body nano-nodes, Nano-Sim (simulator) based on NS3 is used to simulate the nanonetwork composed of randomly deployed nano-nodes [34]. Nano-nodes collect vibration energy through piezoelectric nano generators during the movement. The parameters' value used in the simulations are listed in TABLE II. In simulations, nano-nodes, gateway and nano-routers are deployed in a cuboid with a length of 0.5 m and a diameter of 0.01 m, which simulates the blood vessels of the human body [51]. The proposed routing protocol FGOR with two models is simulated and compared with the

TABLE II: Simulation Parameter Settings

| Parameter | Value |
|--|---------------------------------|
| System parameters | |
| Simulation duration | 15 s |
| Number of nano gateway | 1 |
| Number of nano-routers | 24 |
| Density of nano-nodes | [0.2 – 2] nodes/cm ³ |
| Size of blood vessel | 50 cm ³ |
| Blood flow rate | 10 cm/s |
| Maximum storage energy | 50 pJ |
| Energy-harvesting time slot | 0.1 s |
| Transmission energy consumption/byte | 1.6 * 10 ⁻³ pJ/byte |
| Received energy consumption/byte | 1.6 * 10 ⁻⁴ pJ/byte |
| Energy-harvesting rate | [1 – 5] pJ/s |
| Transmission loss parameter | 0.75 |
| Number of nodes for routing simulation | 10 – 100 |
| Number of nodes for thermal simulation | 100 |
| PHY details | |
| Pulse energy | 100 pJ |
| Pulse duration | 100 fs |
| Pulse Interarrival Time | 10 ps |
| Transmission range of nano-nodes | 0.5 cm |
| Transmission range of nano-routers | 2 cm |
| MAC | |
| Back-off interval | [0 – 100] ns |
| Network Layer | |
| Initial TTL value of data packet | 30 |
| Initial TTL value of probe packet | 1 |
| Message Processing Unit | |
| Data packet size | 100 byte |
| Probe packet size | 30 byte |
| ACK packet size | 10 byte |
| Generation slot of data packet | [2 – 5] s |
| Generation slot of probe packet | 0.1 s |
| Temperature measurement time slot | 0.05 s |

existing Flooding protocol and Random protocol. To evaluate the performance of these protocols, four different common metrics in nanonetworks are adopted. Finally, to prove the biosecurity of the intra-body nanonetworks, a simulation of the temperature variation range of intra-body nano-nodes in blood vessels is also conducted.

A. Successful Packet Transmission Rate

The end-to-end successful packet transmission rate is investigated as the first performance metric for intra-body nanonetworks, which can be defined as:

$$R_s = \frac{N_{received}}{\sum_{i=1}^n N_{sent_i}}, \quad (14)$$

where $N_{received}$ and N_{sent} refer to the number of packets received by gateway and the number of packets sent by nano-nodes in the networks, respectively.

The hops of a packet transmission refer to the times a packet is forwarded from generation to acceptance. The lower the average hops of packet transmission, the relatively less energy is consumed in the whole nanonetwork transmission process. The average hops of packet transmission can be calculated according to the following formula:

$$H_{avg} = \frac{\sum_{i=1}^n N_{t_i}}{N_{rec}}, \quad (15)$$

where H_{avg} denotes the times of packets forwarded by node i throughout the simulation, N_{rec} refers to the total acceptance of the gateway.

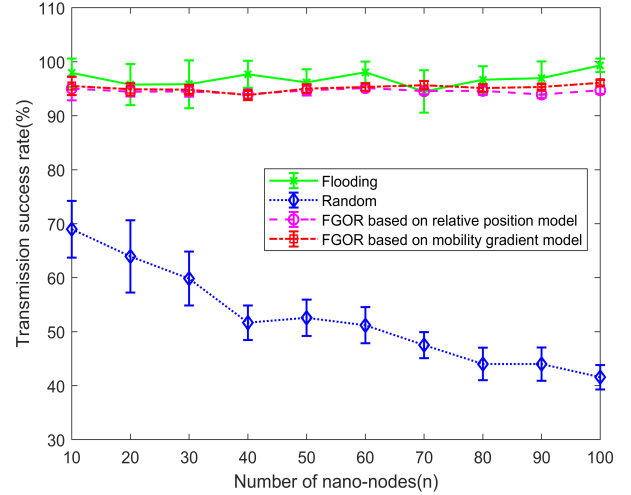


Fig. 11. End-to-end Successful Packet Transmission Rate

As shown in Fig. 11, the probability of successful end-to-end packet transmission rate of FGOR protocol with RP model or MG model is much higher than Random protocol. In detail, on the one hand, compared with Random protocol, the proposed FGOR protocol fully takes advantage of broadcasting characteristics of wireless transmission. Nano-source selects multiple candidate nodes to relay data packets, and forwards packets through priority-based back-off mechanism, which increases the probability of successful packet transmission. On the other hand, FGOR protocol achieved almost the same performance on successful transmission rate with much less overflowing forwarding as shown in Fig. 12, compared with Flooding protocol. Because FGOR establishes a packet forwarding model improving the probability of successful packet forwarding, and also reducing the redundancy of packet forwarding and effectively alleviating network congestion. Compared the performance of FGOR protocol with the two different models, FGOR protocol with MG model has a slight advantage over RP model, as the optimization of CRS criterion by considering the mobility direction of nano-nodes.

B. Average Energy Consumption

Average energy consumption of one successful packet transmission is investigated as the second performance metric for intra-body nanonetworks, which can be calculated as:

$$E_{avg} = \frac{\sum_{i=1}^n E_i}{N_{received}}, \quad (16)$$

where E_i is energy consumption of each node in the nanonetwork.

It can be seen from Fig. 13 that the average energy consumption of FGOR protocols is significantly less than the other two protocols under the same network conditions. The reason is that few nodes are involved in forwarding the duplicated packets by comparing FGOR protocol with Flooding protocol, which reduces the total energy consumption of nanonetworks. Compared with the Random protocol, although randomly choosing a node to forward the packet is beneficial to control

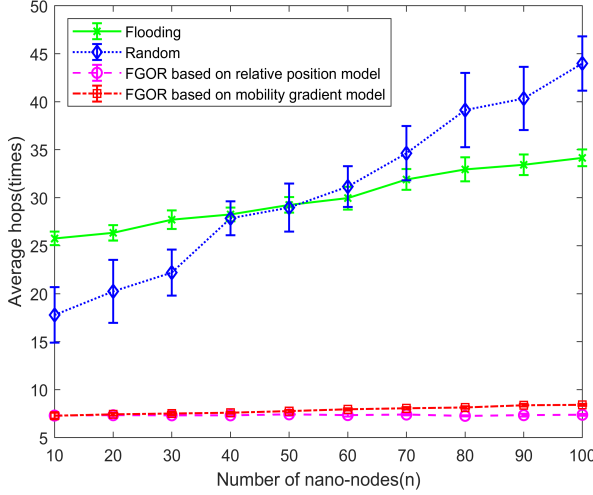


Fig. 12. Average hops of packet transmission

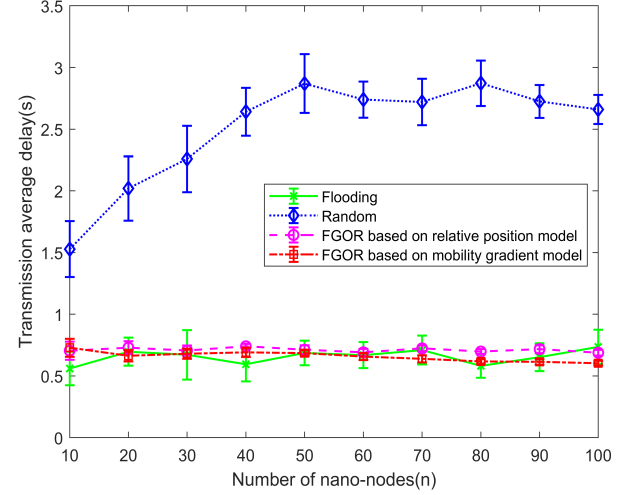


Fig. 14. End-to-end packet transmission delay

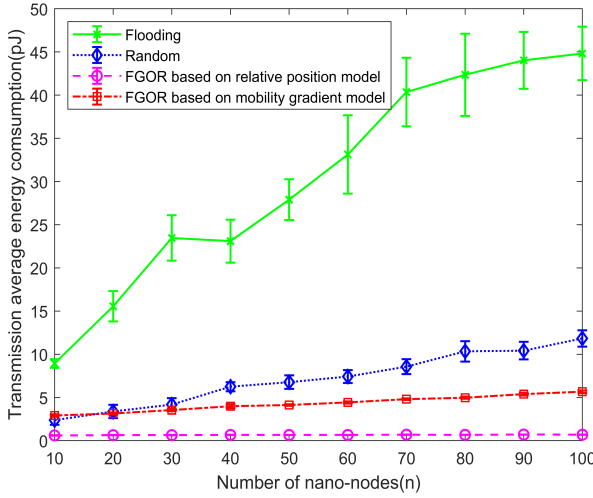


Fig. 13. Average energy consumption of packet transmission

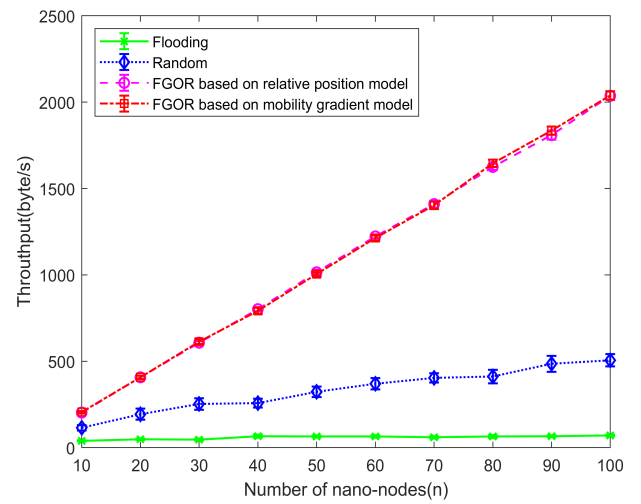


Fig. 15. End-to-end throughput

the duplications, but which will lead to the unawareness of transmission direction, and finally results in an increase in the average energy consumption. It has been shown that FGOR protocol with MG model consumes more energy than FGOR protocol with RP model as receiving and dealing with more reply packets when periodically updating the $\partial Index$ of the surrounding nodes. With the increase of node density, the average energy consumption is also increased, but still less than the other two protocols.

C. Packet Transmission Delay

The end-to-end packet transmission delay is investigated as the third performance metric for intra-body nanonetworks, which is given as follows:

$$Delay = \frac{\sum_{i=1}^n (T_{arrive_i} - T_{send_i})}{N_{sent}}, \quad (17)$$

where T_{arrive_i} and T_{send_i} refer to the arrival time of packet i and the sending time of packet i .

As shown in Fig. 14, the delay of Random protocol is particularly much higher than Flooding protocol and FGOR protocol. The reason is that random node selection for packet forwarding will lose the directionality of data packet transmission, which leads to more unnecessary communications and then increase the packet delay as a result. However, due to the blind forwarding, the delay of Flooding protocol is similar to FGOR protocol. It can be seen that the optimization of CRS with MG model slightly reduces the delay of RP model.

D. Effective Throughput

Effective throughput is investigated as the fourth performance metric in nanonetworks, which can be calculated as follows:

$$Throughput = \frac{B_{total}}{Delay}, \quad (18)$$

where B_{total} refers to the total bytes received by gateway.

The results are given in Fig. 15. It is shown that as the node density increases, the throughput of Random protocol and FGOR protocol are improved with an upward trend. The reason is that the increase of nano-nodes in the network leads to an increase in the number of generated packets and received packets. For the Random protocol, the successful packet transmission rate is lower and the transmission delay is longer, which directly leads to lower throughput. But for the Flooding protocol which has low transmission delay and high successful transmission rate, the overflowing forwarding used excessive nodes for transmitting one information. So the throughput of Flooding protocol can not be enlarged effectively. Moreover, the throughput of FGOR protocol with MG model is similar to RP model.

E. Effect of Heat Energy

The effect of heat energy caused by nano-nodes in the communication process on blood cells can be simulated by the Poisson Point Process model (PPPs). First, energy loss is basically absorbed by the environment and converted into heat, the energy loss of nano-nodes is greater than the generated heat energy and the difference is small. The change in temperature of a certain location in the surrounding environment can be calculated by the following formula [49]:

$$\Delta T = \sum_{k \in \Phi_{\bar{p}}} B_k c_3 \mathcal{G}_k \frac{1}{r_k^2} \approx c_3 g_{mn} \frac{1}{d_0^2}, \quad (19)$$

where B_k is a Bernoulli random variable with parameter $p_L(r_k)$, r_k is the distance from the nearby nano-nodes k to red blood cell. \mathcal{G}_k is antenna gains. g_{mn} is the main antenna gain [52]. d_0 is the distance between the typical cell and the nearest nano-node, because the temperature increase is largely induced by the nearest nano-node. Furthermore, c_3 in the formula of ΔT can be calculated as follows:

$$c_3 = \frac{\sigma_a t_{on} P_t}{4\pi c_c m_c}, \quad (20)$$

where σ_a is the cross-sectional area that absorbs energy, c_c is the cell specific heat capacity, m_c is the cell mass. t_{on} is the duration of the transmission, P_t is the transmission power of nano-nodes.

While nano-nodes randomly move through blood vessel, PPPs model is used to simulate and calculate the temperature increase on certain point near a blood cell. Since the gateway consumes a large amount of energy during the communication process of sending and receiving data packets, it may generate more heat. Therefore, the sampling range is selected near the gateway. As shown in Fig. 16, over 99% possibility of the temperature increase is much less than the body temperature difference over time. According to the cumulative distribution function, it is ensured that the temperature changes are within an acceptable range. The simulations have approved that intra-body nano-nodes network does not affect the safety of the human body.

V. CONCLUSION

In this paper, combined with the application scenarios of blood vessels in the human body, an opportunistic routing protocol based on flow guidance for mobile intra-body

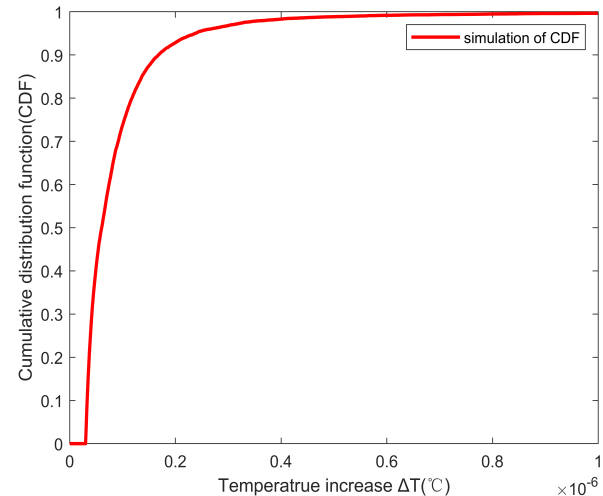


Fig. 16. CDF of temperature increase

nanonetworks is proposed with RP model and MG model, which are based on the index metric and one candidate node selection mechanism with competitive back-off, respectively. The simulation results demonstrate that the proposed FGOR protocol has a similar end-to-end packet transmission success rate and average packet transmission delay as the Flooding protocol and outperforms the Random protocol. Meanwhile, it has better performance in terms of average packet transmission energy and throughput compared to the other two protocols, which is meaningful for real intra-body applications. Moreover, the simulation of the resulting temperature indicates that the nano-nodes can be utilized in intra-body communication without having any severe effect on the body cells. The two models of FGOR protocol have their benefits, but for the nanonetworks with self-organizing energy harvesting ability, the FGOR protocol with MG model is more advantageous.

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