FGOR: Flow-Guided Opportunistic Routing for Intrabody Nanonetworks

Xin-Wei Yao, *Member, IEEE*, Yi-Wei Chen, Yi Wu, Kai Zhao, and Josep M. Jornet, *Senior Member, IEEE*

***Abstract*—The advancement of nano communication has opened the door for the development of intrabody medical application services. Flow-guided nano-communication networks have gained major attraction in recent years as an effective solution for intrabody sensing and actuation. This article builds a three-layer vertical network structure for intrabody nanonetworks, i.e., nano nodes, nano routers, and gateway, where data packets generated by nano nodes are relayed to the 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 intrabody nanonetworks in a single-flow environment where the nano devices are restricted, a flow-guided opportunistic routing (FGOR) protocol 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 the 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 RP information of nodes to perform backoff forwarding for decreasing transmission redundancy. Simulation results show that the RP model improves the throughput and significantly extends the lifecycle of intrabody 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 the circulation environment of intrabody.**

***Index Terms*—Candidate relay selection (CRS), intrabody nanonetworks, mobility gradient (MG) model, opportunistic routing, relative position (RP) 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 nanosensors, 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 the human body (such as blood vessels) to satisfy specific requirements [6]–[8]. Without loss of generality, in this article, a nanonetwork composed of multiple nano nodes in the circulatory system of the human body is called a flow-guided intrabody 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 an excellent data rate and uses less energy per bit. The attenuation of the electromagnetic signal in the THz band is very large, especially in the human body [14]–[17]. Consequently, high path loss (including spreading loss and absorption loss) limits the communication range of nano nodes [18]–[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 macrodevice (wearable device or smartphone). Through a hierarchical structure based on the function of devices, higher efficiency and wider coverage can be achieved. Finally, intrabody 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, and 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] and [22]. It follows a vertical distribution structure and consists of three different devices [23]–[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

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Xin-Wei Yao is with the School of Computer Science and Technology and the Institute for Frontier and Interdisciplinary Sciences, Zhejiang University of Technology, Hangzhou 310023, China (e-mail: xwyao@zjut.edu.cn).

Yi-Wei Chen, Yi Wu, and Kai Zhao are with the School of Computer Science and Technology, Zhejiang University of Technology, Hangzhou 310023, China (e-mail: 2111912109@zjut.edu.cn; 201806010306@zjut.edu.cn; 15779170697@163.com).

Josep M. Jornet is with the Department of Electrical and Computer Engineering, Northeastern University, Boston, MA 02115, USA (e-mail: j.jornet@northeastern.edu).

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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

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]: 1) 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 and 2) through multihop 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]. 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 article 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. Xu *et al.* [31] 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 article 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, an 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 RP 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. The index reflects the RP between nano node and gateway, since nodes with greater index are theoretically closer to the gateway. Furthermore, the related candidate relay selection (CRS) criterion could be established based on the RP information.

C. Mobility Gradient (MG) Model

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

D. Backoff Forwarding Mechanism

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

The remainder of this article is organized as follows. In Section II, we present the existing related studies in nanonetworks. In Section III, we propose the flow-guided opportunistic routing (FGOR) protocol, including two models, related CRS criteria, and a candidate node forwarding mechanism. In Section IV, we provide a performance evaluation for the proposed protocol under different conditions, and the security of nano nodes implanted in the human body is verified. Finally, in Section 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 nanosensor networks (WNSNs) was proposed to optimize the utilization of harvested energy in [25]. Liu *et al.* [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. Büther *et al.* [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 (EBCR) protocol 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. Yao *et al.* [37] proposed an energy-efficient cooperative routing algorithm with optimal link cost, which is based on a cooperative communication model for hierarchical cluster-based nanonetworks. However, this routing algorithm was unsuitable for a flow-guided intrabody environment.

In [23] and [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 [25], [26], [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 intrabody mobile nanonetworks. Stelzner *et al.* [38] analyzed the characteristics of intrabody 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 nanosensor networks in the human body.

B. Location-Aware Routing Protocols in Mobility Environment

Because of the high mobility of nano nodes, intrabody 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 networks 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 newly available nodes. And this article 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 (GPSs). 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 multihop 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 intrabody nanonetworks. Rikhtegar *et al.* [41] proposed a fuzzy logic-based mobility management (FLMM), which uses the distance from the nano controller to nano nodes as local parameters. But this distance is calculated on the assumption of nano nodes linearly moving in random directions with a constant velocity. And this FLMM is not appropriate for intrabody 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. The 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 nanogenerators. From the energy analysis of nanonetworks in [44], the expression of the energy collected by the piezoelectric nanogenerators can be derived, which is about the function of time (t) and the maximum storable energy of the nano-node capacitor Q_{MAX} [45]

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

where Δc is the electric charge (calculated in coulombs) generated during the compression release cycle of the piezoelectric nanogenerator, v_g refers to the voltage induced by the nanogenerator during the compression release cycle, and f is the frequency of the compression release cycle. According to the values used in [43] and [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

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

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

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

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

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

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

$$q_h(q) = \lambda_h(q) \cdot T. \tag{5}$$

D. Effect of Temperature Rising Caused by Nanonodes

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 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] and [47]. A basic physical mechanism behind the molecular absorption noise was introduced in [48]. Further research in [49], the photothermal effect on red blood cells induced by electromagnetic waves of communications between nodes can be simulated through stochastic geometry. Elayan *et al.* [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. Elayan *et al.* [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 effection 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 the FGOR Protocol

Without loss of generality, in this article, a blood vessel is selected as one example of intrabody 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 the 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 the FGOR protocol in this section.

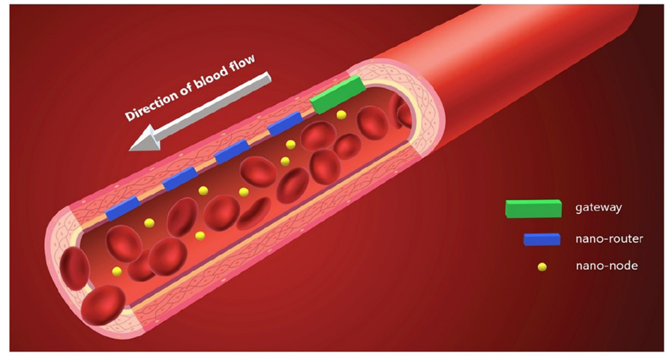


Fig. 1. Whole picture of network.

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 the 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 indices stored in their memories according to the probe packets, other nano nodes outside the communication range keep their indices, so the nano nodes closer to the gateway always have higher index values. 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 the forwarding strategy in the FGOR protocol is shown in Fig. 2. Nanosource 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

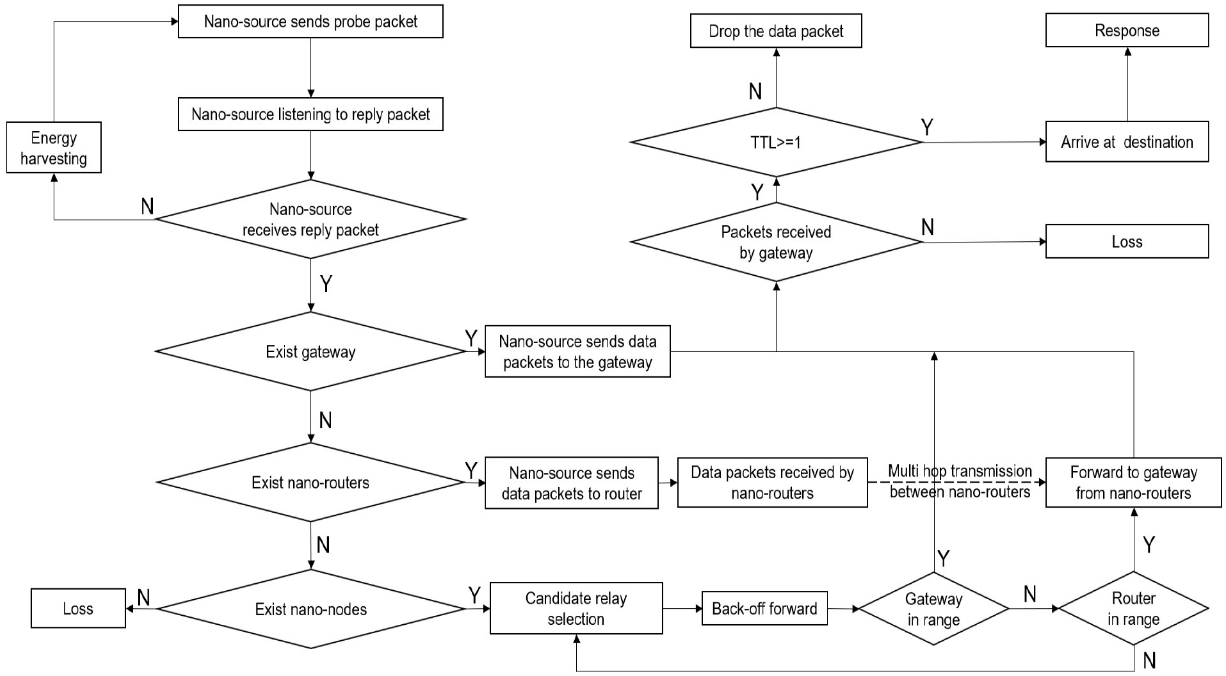


Fig. 2. Flowchart of the FGOR protocol.

Source	Destination	TTL	PacketId	Index	NodeId	Tag

Fig. 3. Header format of data packet with the RP model.

Source	Destination	TTL	PacketId	Index	NodeId	NodeEnergy

Fig. 4. Header format of reply packet with the RP model.

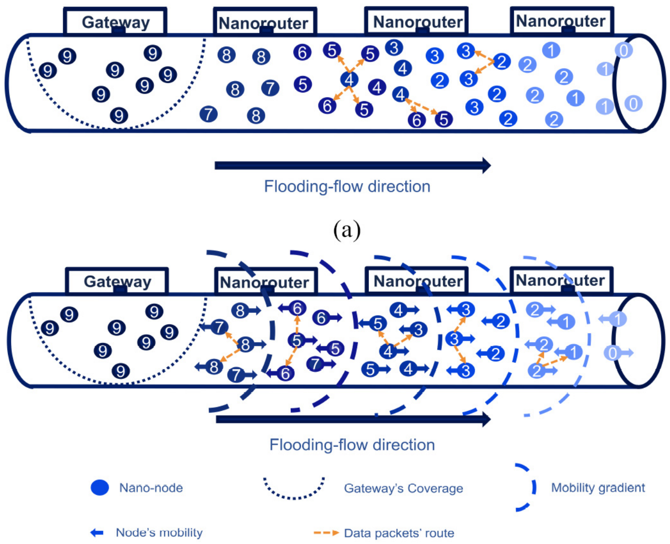
index value with the index value of the received probe packet and sends back a reply packet (the header of the reply packet is shown in Fig. 4). The source node updates the *tag.type* in the data packet according to the NodeId in the successfully received reply packet. If there is a nano router in neighbors, the *tag.type* of the 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 sections, 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. Nanosource sends out the real data packet after setting *tag.type*. Then, neighbors receive the data packet from nanosource and decide to store or discard the data packet according to the *tag.type* of the received data packet. If *tag.type* equals 1, nano router keeps the packet and forwards it to adjacent nano routers in multihop transmission. Other neighbors discard the data packet. If *tag.type* equals to 2, nano node will conduct the backoff 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 sections, two CRS models (i.e., RP model and MG model) for mobile intrabody nanonetworks are proposed to effectively establish the related CRS.

B. Relative Position Model

In mobile nanonetworks, the mobility of nano nodes has a great impact on the performance of nanonetworks. Nevertheless, the deployment of traditional position sensors (such as GPS) is impossible in nanoscaled 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 article, the RP between mobile nodes and stationary gateway is first considered by sending signals to inform the nodes in the communication range. The nano nodes flowing through the gateway will receive the updated signals successively in the blood with unidirectional fluidity. After a period of time, the value of the signal can be used to represent the distance between the nano node and gateway. It means that the 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 RP meaningful. Based on this idea, an RP model of nano nodes in mobile nanonetworks based on flow guidance is designed.

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.



(a)

(b)

Fig. 5. (a) RP model and (b) MG model.

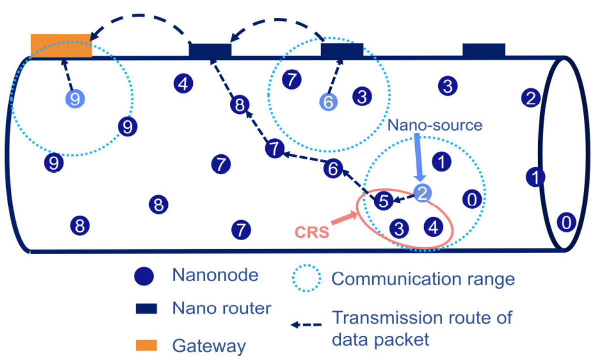


Fig. 6. CRS of the RP model.

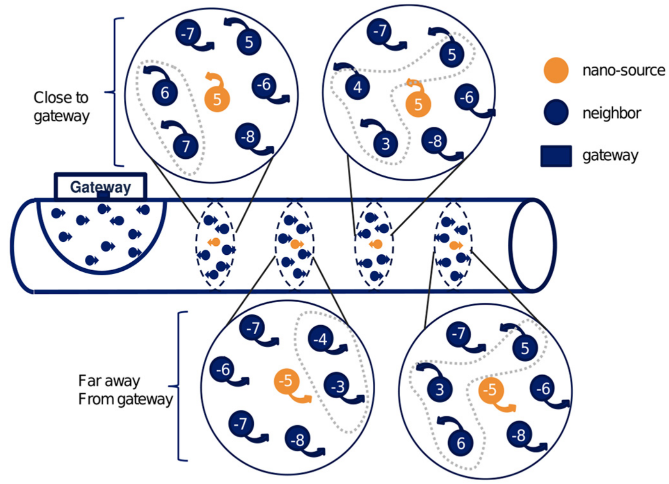


Fig. 7. CRS of the MG model.

The node does not change the index value before receiving the probe packet, and its initial value of the 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. The packet will be discarded when TTL turns to 0. So TTL of the probe packet is set to 1 to prevent nano nodes from forwarding the probe packet.

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

C. Mobility Gradient Model

The RP 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), nanosource transmits data packets to the neighbors with higher index according to the CRS criterion, but their RP to the gateway is much farther than the 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 candidate selection. So in this section, a more comprehensive and precise model (i.e., the MG model) is designed and proposed based on the above RP model.

As shown in Fig. 5(b), the index value of the 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 the movement, and the direction of movement relative to the gateway can be regarded as another criterion of CRS. In one cycle, nanosource obtains the index of surrounding nano nodes and calculates the average index $\overline{\text{Index}}$. According to the change of gradient information in one cycle, the nano node can calculate its own relative MG as follows:

$$\partial\overline{\text{Index}} = \frac{\Delta\overline{\text{Index}}}{\Delta t} \tag{6}$$

where $\Delta\overline{\text{Index}}$ 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 $\partial\overline{\text{Index}}$ 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 intrabody 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 nanosource nodes in two cases and four situations are presented as follows.

1) When a nanosource node is approaching the gateway, neighbors moving faster than the nanosource toward the gateway are selected as relay candidates. If there

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

Fig. 8. Header format of data packet with the MG model.

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

Fig. 9. Header format of reply packet with the MG model.

```
Start
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 ← 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. CRS strategy.

is no neighbor moving toward the gateway faster than nanosource, neighbors moving toward the gateway are selected as relay candidates. If there is no neighbor moving toward the gateway, the relay candidate set is empty.

2) When nanosource is moving away from the gateway, neighbors moving toward gateway are selected as relay candidates. If there is no neighbor moving toward the gateway, neighbors moving away from the gateway slower than nanosource are selected as relay candidates. If there is no neighbor moving away from the gateway slower than the nanosource, the relay candidate set is empty.

Noted that the header formats of different packets with MG model are different as shown in Figs. 8 and 9. Moreover, the corresponding pseudo code is shown in Fig. 10. In detail, $\boldsymbol{S}$ refers to source node carrying data packet, and $\boldsymbol{V}$ refers to nano nodes. $\boldsymbol{S}$ finds neighbor nodes marked $\boldsymbol{N_i}$ and sends probe packets to $\boldsymbol{N_i}$. From the reply packet provided by $\boldsymbol{N_i}$, $\boldsymbol{S}$ will execute different options according to NodeId value in reply packet. The *tag.type* is also updated in the header of data packet.

D. Candidate Node Backoff Forwarding Mechanism in Mobile Nanonetwork

As nano nodes with high density coexist in intrabody 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 backoff forwarding according to the priority after receiving data. Specifically, when the candidate nodes with different priorities start the backoff 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 backoff 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 backoff time T_{b-o} of the candidate v_i in the set is related to the energy-harvesting rate, residual energy, and $\overline{Index}$ and $\partial\overline{Index}$ of the node according to the MG model. The backoff time T_{b-o} follows an exponential distribution, whose probability density function [31] can be expressed:

$$f_{T_{b-0}}(t) = \frac{1}{\lambda(v_i)} e^{-\frac{t}{\lambda(v_i)}} \tag{7}$$

where $\lambda(v_i)$ is the average backoff time of v_i, which is the function of selection metric

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

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

$$M_{vi} = \lambda_1 \text{RE} + \lambda_2 \text{Index}_n. \tag{9}$$

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

$$M_{v_i} = \lambda_1 RE + \lambda_2 \partial\overline{\text{Index}} + \lambda_3 \overline{\text{Index}} \tag{10}$$

where λ_1, λ_2, and λ_3 are all system parameters. RE is the survival model of candidates

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

where μ is the system parameter and $E_{\max}$ is the maximum energy. According to the prototype design and the corresponding circuit model of the piezoelectric nanogenerator, 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

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

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

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

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	$0.05\ s$

where ΔE is the energy increment of the capacitor, t_{cyc} is the cycle time, and 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 intrabody mobile nanonetworks and the biosecurity of intrabody 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 nanogenerators during the movement. The parameters' value used in the simulations is 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 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 intrabody nanonetworks, a simulation of the temperature variation range of intrabody 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 intrabody nanonetworks, which can be defined as follows:

$$R_s = \frac{N_{\text{received}}}{\sum_{i=1}^{n} N_{\text{sent}_i}} \tag{14}$$

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:

$$H_{\text{avg}} = \frac{\sum_{i=1}^{n} N_{t_i}}{N_{\text{rec}}} \tag{15}$$

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

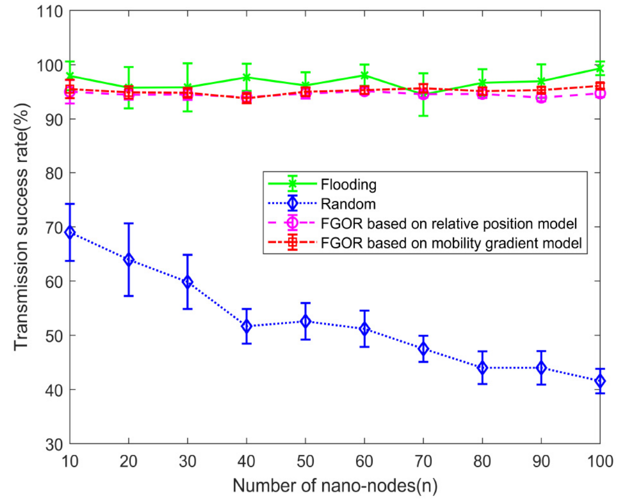


Fig. 11. End-to-end successful packet transmission rate.

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

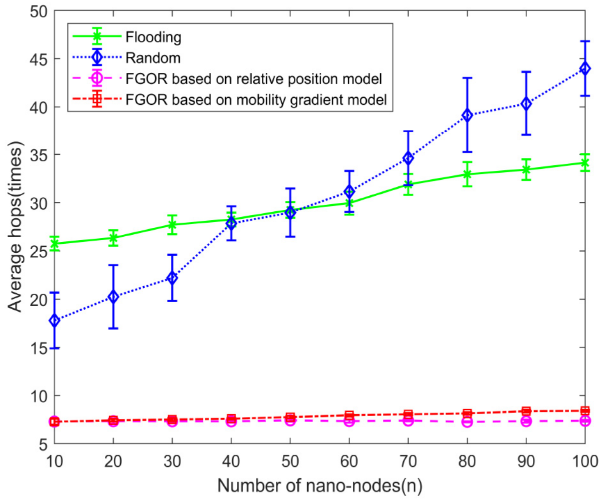


Fig. 12. Average hops of packet transmission.

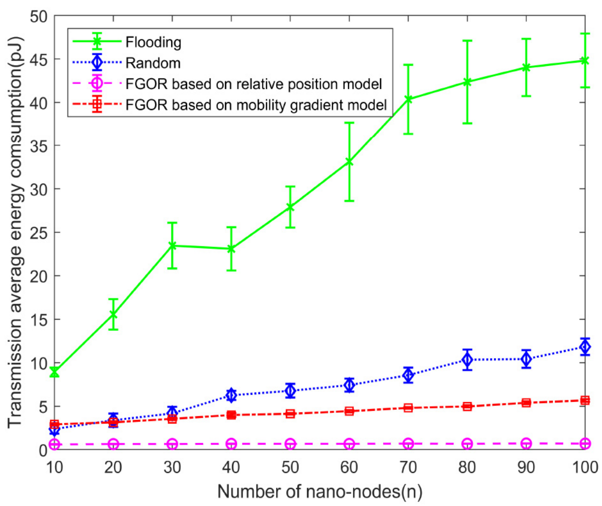


Fig. 13. Average energy consumption of packet transmission.

B. Average Energy Consumption

The average energy consumption of one successful packet transmission is investigated as the second performance metric for intrabody nanonetworks, which can be calculated as follows:

$$E_{\text{avg}} = \frac{\sum_{i=1}^{n} E_i}{N_{\text{received}}} \tag{16}$$

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 the FGOR protocol with the 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 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 the FGOR protocol with the MG model consumes more energy than the FGOR protocol with the RP model as receiving and dealing with more reply packets when periodically updating the $\overline{\partial \text{Index}}$ 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.

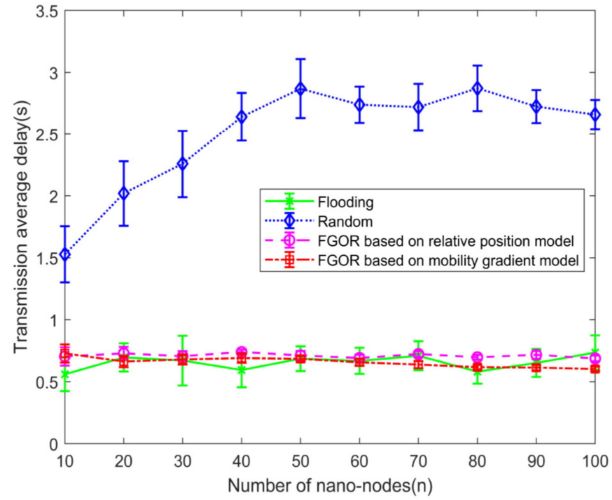


Fig. 14. End-to-end packet transmission delay.

C. Packet Transmission Delay

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

$$\text{Delay} = \frac{\sum_{i=1}^{n} \left(T_{\text{arrive}_i} - T_{\text{send}_i}\right)}{N_{\text{sent}}} \tag{17}$$

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 the Random protocol is particularly much higher than the 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 the Flooding protocol is similar to the FGOR protocol. It can be seen that the optimization of CRS with the MG model slightly reduces the delay of the RP model.

D. Effective Throughput

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

$$\text{Throughput} = \frac{B_{\text{total}}}{\text{Delay}} \tag{18}$$

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 the Random and FGOR protocols are improved with an upward trend. The reason is that the increase of nano nodes in the network

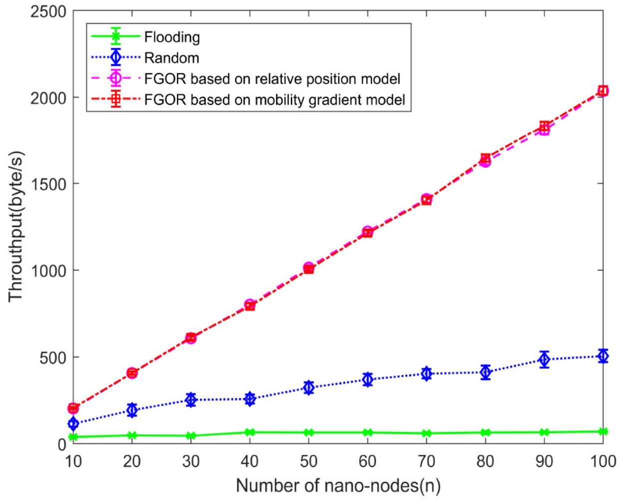


Fig. 15. End-to-end throughput.

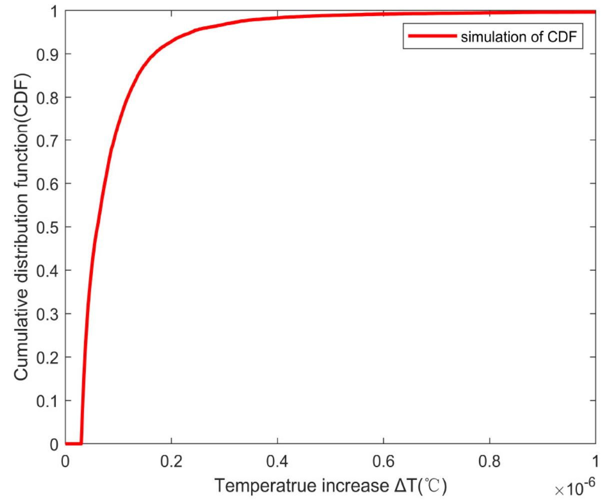


Fig. 16. CDF of temperature increase.

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 the Flooding protocol cannot be enlarged effectively. Moreover, the throughput of the FGOR protocol with the MG model is similar to the 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 (PPPs) model. 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]:

$$\Delta T = \sum_{k \in \Phi \overline{p}} B_k c_3 \mathcal{G}_k \frac{1}{r_k^2} \approx c_3 g_{mn} \frac{1}{d_0^2} \tag{19}$$

where B_k is a Bernoulli random variable with parameter $p_L(r_k)$, and 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:

$$c_3 = \frac{\sigma_a t_{\text{on}} P_t}{4\pi c_c m_c} \tag{20}$$

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

While nano nodes randomly move through the blood vessel, the PPPs model is used to simulate and calculate the temperature increase on a 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 the intrabody nano-nodes network does not affect the safety of the human body.

V. CONCLUSION

In this article, combined with the application scenarios of blood vessels in the human body, an opportunistic routing protocol based on flow guidance for mobile intrabody nanonetworks is proposed with the RP and MG models, which are based on the index metric and one candidate node selection mechanism with competitive backoff, 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 intrabody applications. Moreover, the simulation of the resulting temperature indicates that the nano nodes can be utilized in intrabody communication without having any severe effect on the body cells. The two models of the FGOR protocol have their benefits, but for the nanonetworks with self-organizing energy-harvesting ability, the FGOR protocol with the MG model is more advantageous.

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Xin-Wei Yao (Member, IEEE) received the B.S. degree in mechanical engineering and the Ph.D. degree in information engineering from Zhejiang University of Technology, Hangzhou, China, in 2008 and 2013, respectively.

He is currently a Professor with the School of Computer Science and Technology and the Vice Dean of the Institute for Frontier and Interdisciplinary Sciences, Zhejiang University of Technology. From March 2012 to February 2013, he was a Visiting Scholar with Loughborough University, Loughborough, U.K. From August 2015 to July 2016, he was a Visiting Professor with the University of Buffalo, The State University of New York, Buffalo, NY, USA. His current research interests are in AIoT, Internet of Nano Things, smart crowdsensing and colaboration, terahertz-band communication networks, and electromagnetic nanonetworks. In these areas, he has coauthored more than 100 peer-reviewed scientific publications and four books and has also been granted more than 20 Chinese patents.

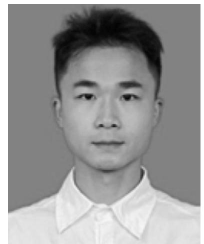
Prof. Yao was the recipient of the Wu Wen-Jun Artificial Intelligence Excellent Youth Award, and more than six Prices of Technological Invention from the Chinese Government. He has served on technical program committees of many IEEE/ACM conferences. He is a member of ACM.

Yi-Wei Chen received the B.E. degree from Jiangsu Ocean University, Lianyungang, China, in 2019, and the M.S. degree from the College of Computer Science and Technology, Zhejiang University of Technology, Hangzhou, China, in 2022, where she is currently pursuing the Ph.D. degree from the College of Computer Science and Technology.

Her current research interests are communication protocols for intrabody nanonetworks and modeling of Terahertz communication. In these areas, she has co-edited one book and has granted one patent in China.

Yi Wu received the B.E. degree from the College of Computer Science and Technology, Zhejiang University of Technology, Hangzhou, China, in 2022.

He is actively working on follow up research for a conference paper. His current research interests focus on intrabody nanonetworks, terahertz communication, and knowledge graphs. In these research areas, he has granted two patents in China.



Kai Zhao received the B.E. degree from Yichun University, Yichun, China, in 2018, and the M.S. degree with the College of Computer Science and Technology, Zhejiang University of Technology, Hangzhou, China, in 2022.

His current research interests are wireless networks, communication protocols for intrabody nanonetworks, and routing protocols for flow-guided nanonetworks. In these areas, he has co-edited one book and has granted two patents in China.

Josep M. Jornet (Senior Member, IEEE) received the B.S. degree in telecommunication engineering and the M.Sc. degree in information and communication technologies from the Universitat Politecnica de Catalunya, Barcelona, Spain, in 2008, and the Ph.D. degree in electrical and computer engineering from Georgia Institute of Technology, Atlanta, GA, USA, in 2013.

From September 2007 to December 2008, he was a Visiting Researcher with the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, under the MIT Sea Grant program. Between August 2013 and August 2019, he was a Faculty with the Department of Electrical Engineering, University at Buffalo, The State University of New York, Buffalo, NY, USA. Since August 2019, he has been an Associate Professor with the Department of Electrical and Computer Engineering, Northeastern University, Boston, MA, USA. His current research interests are in terahertz-band communication networks, wireless nano-bio-communication networks, and the Internet of Nano Things. In these areas, he has coauthored more than 120 peer-reviewed scientific publications and one book and has also been granted three U.S. patents.

Dr. Jornet is a recipient of the National Science Foundation CAREER Award and several other awards from IEEE, ACM, and UB. Since July 2016, he has been the Editor-in-Chief of the *Nano Communication Networks Journal* (Elsevier). He is serving as the Lead PI on multiple grants from U.S. federal agencies, including the National Science Foundation, the Air Force Office of Scientific Research, and the Air Force Research Laboratory.