

Retraction

Retracted: Physarum-Inspired Autonomous Optimized Routing Protocol for Coal Mine MANET

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This article has been retracted by Hindawi following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of one or more of the following indicators of systematic manipulation of the publication process:

- (1) Discrepancies in scope
- (2) Discrepancies in the description of the research reported
- (3) Discrepancies between the availability of data and the research described
- (4) Inappropriate citations
- (5) Incoherent, meaningless and/or irrelevant content included in the article
- (6) Peer-review manipulation

The presence of these indicators undermines our confidence in the integrity of the article's content and we cannot, therefore, vouch for its reliability. Please note that this notice is intended solely to alert readers that the content of this article is unreliable. We have not investigated whether authors were aware of or involved in the systematic manipulation of the publication process.

Wiley and Hindawi regrets that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our own Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

References

- [1] H. Jiang, X. Liu, S. Xiao, C. Tang, and W. Chen, "Physarum-Inspired Autonomous Optimized Routing Protocol for Coal Mine MANET," *Wireless Communications and Mobile Computing*, vol. 2020, Article ID 8816718, 14 pages, 2020.

Research Article

Physarum-Inspired Autonomous Optimized Routing Protocol for Coal Mine MANET

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Mobile Ad Hoc Network (MANET) is suitable for complex environment communication in coal mine. The processes of nutrient flux transfer and path choice in Physarum networks are similar to data transmission and routing decision in MANET. In this paper, we use a Physarum optimization model to design Physarum-inspired autonomous optimized routing (PIAOR) protocol to adapt to the dynamic network topology in underground mine. PIAOR introduces the status of MANET into the Poisson equation in the Physarum model, selects reasonable parameters to represent the transmission performance of the network, and uses the differential evolution equation of the Physarum model to evolve the parameters. PIAOR has achieved the distributed routing decision by automatically reconstructing the optimal routing path, which has reduced the algorithm complexity. Based on NS2, simulation experiments are performed to evaluate the performance of PIAOR, and the results are compared with GPSR, PIMAR, and P-IRP routing algorithms. The experimental results show that the routing path selected by PIAOR is better than that selected by the other three protocols in the performance of average end-to-end delay, delivery ratio, and throughput. The balance of energy consumption and network load is reached, and the network lifetime is effectively prolonged when using the PIAOR protocol.

1. Introduction

Most of the coal mines consist of narrow and long tunnels, and the environment is harsh. The operation and production in coal mines are complicated. There are a lot of infrastructures in traditional networks, which make the deployment and management of equipment troublesome and not suitable for harsh environments and mobile operation scenarios. With the continuous coal mining and working-face driving, wireless base stations or access points may have not been deployed in some coal mining areas. At the same time, affected by the complex communication environment in the underground mine, the coverage of the base station is limited, which makes it easier for blind monitoring areas to form and makes it impossible to upload the collected monitoring information. In order to ensure the safety of coal mines, it is necessary to upload the collected data in real time to prevent disasters such as gas leakage. Therefore, it is necessary to propose new wireless communication methods to satisfy

the requirements of coal mine safety monitoring in special areas and to improve the adaptability of the communication networks in highly complex environments. Mobile ad hoc network (MANET) is different from traditional wireless networks. It does not rely on any infrastructure and has no central nodes, and each node is mobile. It can dynamically self-organize into a network, which can meet the deployment requirements of wireless networks in special areas in underground mines [1].

MANET [2] are collections of wireless mobile nodes, constructed dynamically without the use of any existing network infrastructure or centralized administration. Each node in a MANET can act as a router or a forwarding node. Nodes can leave and join the network at any time without disrupting the communication of other nodes. MANET's self-organization and self-adaptation allow nodes to fail, which will improve the network stability and facilitate efficient network deployment. Most of the network topologies in coal mines are long-chain structure, which significantly

increases the communication hops and exacerbates the instability of multihop communications. Therefore, it poses new challenges to the routing protocols of MANET in the underground mine. In addition, since the intelligent terminal nodes in the coal mine are mostly powered by batteries, their energy is limited. Their locations are changing constantly with the movement of miners and working-face driving. As the result, the topology and performance of MANET in the mine are changing dynamically. Routing decisions need to adapt to changes in network status timely, considering the influence of factors such as energy consumption, buffer occupation of nodes, and link state, to maintain stable and efficient data transmission.

Physarum is a kind of protoplast slime fungus, which is characterized by no single cells and gathering towards food sources. Physarum can extend to scatter food sources, cover food sources to the greatest extent, and form a network of tubes among food sources to transmit nutrients and chemical signals. With the change of nutrients in the food source, it is able to disassemble and reassemble the tube structure as well as alter the tube thickness to adapt to the external conditions. The tubes grow bigger when transporting lots of nutrients, while the tubes that do not convey sufficient nutrients gradually shrink and eventually vanish from the network.

Inspired by the mathematical model of the Physarum foraging process [3, 4], this paper proposes to apply the Physarum model to the path optimization process in mobile ad hoc networks and design a Physarum-inspired autonomous optimized routing (PIAOR) protocol for MANET in an underground mine. Parameters such as the energy consumption, the buffer occupation, the distance among nodes, and the mobility of the nodes are used as routing metrics to select the next hop. Mobile terminals are mainly powered by batteries with limited energy. As the network runs, the cache of nodes constantly changes. In the underground mine heterogeneous space, the greater the distance between adjacent nodes, the less easy it is to transmit data. Due to the mobility of the mine nodes, the availability of the link is another important factor in the route construction of the dynamic network. The above parameters change dynamically with the operation of the network. Based on the analysis of the parameters' characteristics, considering both routing efficiency and energy equilibrium, this paper introduces the differential evolution equation of the Physarum algorithm to dynamically adapt to the changes of network environment, which will achieve the optimal selection of the next hop to realize data transmission.

2. Related Work

With the development of MANET, the research on routing protocols is also advancing. Routing protocols fall into three categories: active routing, reactive routing, and hybrid routing. Some routing protocols are improved based on link state and distance vector [5]. However, there are some problems with typical MANET routing protocols. Researchers often consider the residual energy and hop number of nodes in routing decisions and ignore some important, dynamic network information. With the continuous data transmission,

the data packet delivery ratio is greatly reduced [6]. In addition, the collected data usually have a certain degree of redundancy. Data redundancy will cause unnecessary burden on the network. To improve data quality and reduce unnecessary data transmission, it is necessary to think the cache occupation of network nodes and optimize routing decisions [7, 8]. Therefore, adaptive MANET routing protocols should consider and respond to dynamic factors of network performance, such as congestion and link availability of network.

GPSR [9] is a famous greedy routing protocol, which makes greedy forwarding decisions using only information about a router's immediate neighbors in the network topology. P-IRP [10] is a routing protocol that can achieve the trade-off between routing efficiency and energy balance. It can use the node position and residual energy to select the next hop for data transmission, which is applied to the scenario of mobile node. The design of routing protocol for coal mine MANET should consider the influence of dynamic factors, such as node energy and buffer occupation, so as to achieve efficient data transmission and extended network lifetime.

In recent years, the bionic algorithms have provided inspiration to solve many complex problems. The intelligent behavior of natural organisms, such as self-organization and self-optimization, has received more and more attention [11]. Classic bionic algorithms include the ant colony algorithm [12], genetic algorithm [13], and particle swarm optimization algorithm [14].

Based on the characteristics of the Physarum model with robust fault tolerance, high efficiency, and low calculation cost, many researchers use this model to design efficient routing and reliable networks [15, 16]. For example, Nakagaki et al. [17, 18] found that the Physarum model can solve the maze problem in the biological experiment. It can extend from the food source at the entrance to the food source at the exit of the maze. The tubes between food sources become wider as they absorb nutrients, and the remaining tubes gradually shrink to disappear. At the result, the remaining tube was the shortest tube between the inlet and the outlet. Tero et al. [19, 20] places food sources in a simulated Tokyo terrain, eventually forming a network that connects all food sources; the network was comparable to the real railway network of Tokyo in the aspects of efficiency, fault tolerance, and cost. Physarum models have been used to solve many complex graph optimization problems, such as path construction [21], Steiner tree problem [22], and supply chain network design [23]. The routing algorithm based on the Physarum model can select the optimal path in data transmission and shows excellent intelligence in network analysis and design. The autonomous optimization behavior of the Physarum model can effectively solve the routing problem in coal mine MANET. The routing protocol for hybrid wireless mesh networks based on the Physarum model was proposed in [24], which can achieve energy balance and load balance of the wireless mesh networks in underground mines. Intelligent terminals in the coal mine have limited energy and cache. The routing protocol based on the Physarum model can select the node with higher remaining energy and cache as the next hop from neighbor nodes for data transmission,

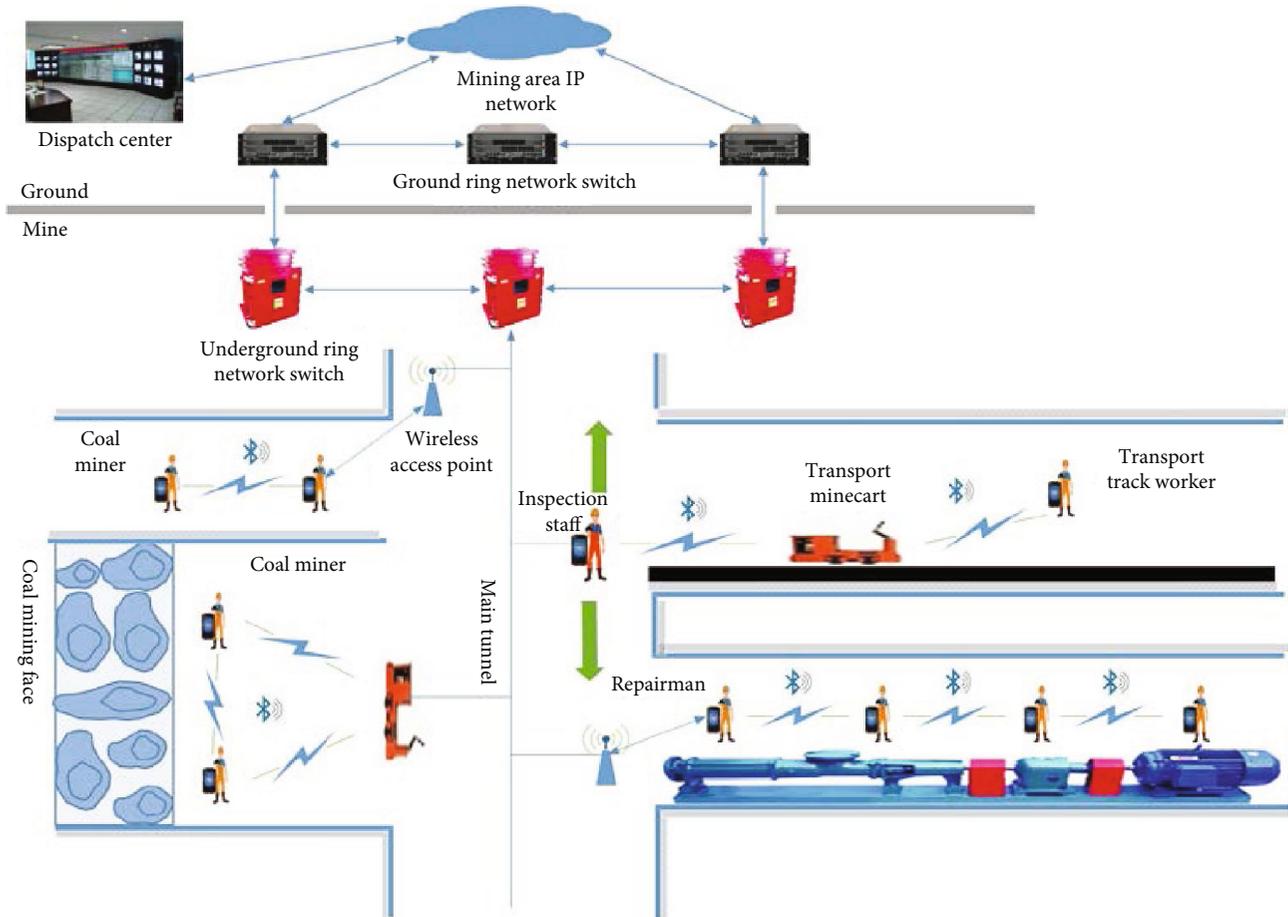


FIGURE 1: Overall view of the mine MANET.

avoiding energy exhaustion or congestion. However, it does not consider node mobility, and it is difficult to adapt to frequent changes in network topology.

Intelligent mobile terminals for coal mines can be connected with each other to build MANET and support the transmission of multimedia information, such as voice and video. Compared with traditional wired networks, MANET in underground mine is easy to deploy and maintain. It can accept nodes at any time and expand the communication range, which is of great significance to build a full coverage sensing network with wireless self-organizing and distributed sensing capability [25]. The topology and status of coal mine MANET change frequently. Autonomous optimized routing protocols should adapt to changes in network parameters in a timely manner. The path selection in nutrient transmission of Physarum is the same as the data transmission and routing in MANET. The Physarum model has superior performance in autonomous optimization and path selection for its outstanding adaptability, so we have designed PIAOR for the coal mine MANET. In the routing decision process, the routing criterion uses the information of local nodes and takes into account the influence of energy, cache, and link status of nodes. This algorithm combines the adaptive adjustment strategy based on node resources and network topology to improve the adaptability of routing decision to network state

change. In addition, the algorithm achieves energy balancing and load balancing with superior throughput and small transmission delay.

3. Preliminaries

3.1. Network Structure. The nodes in the coal mine MANET are randomly distributed in the tunnels or other working areas, which usually follow a certain pattern of movement, as showed in Figure 1. In order to simplify the system model, we make some assumptions shown as follows.

- (i) The physical location of each node can be obtained through a positioning system or device
- (ii) Each node can read the residual energy information from the physical interface and pass up to its network layer
- (iii) Nodes use the whole antenna and have equal transmission radius, which means that the radio channel is bidirectional and symmetrical

In order to simulate the actual application scenario of the coal mine, the network is divided into small regions. Each node belongs to only one region, and each region has a

central node and multiple edge nodes. As showed in Figure 2, node s represent the data source node, and its one-hop communication range is a circular area with r as its radius. Node s needs to find the optimal next-hop node within its one-hop range to send data to the destination node d . $\theta_{j sd}$ represents the measured value where node j deviates from node s to node d . L_{sj} denotes the distance from node s to node j , and $L_j' d$ denotes the projection distance of node j relative to the destination node d . The physical location of each node can be obtained through the positioning system during the network initialization phase. L_{sj} and $\theta_{j sd}$ can be calculated by the following formulas:

$$\begin{aligned} L_{sj} &= \sqrt{(x_s - x_j)^2 + (y_s - y_j)^2}, \\ \theta_{j sd} &= \arccos \frac{L_{sj}^2 + L_{sd}^2 - L_{jd}^2}{2 \times L_{sj} \times L_{sd}}, \end{aligned} \quad (1)$$

where (x_s, y_s) and (x_j, y_j) are the position coordinates of node s and node j , respectively. Therefore, the projection distance $L_j' d$ can be expressed as

$$L_j' d = L_{sd} - L_{sj} \cos \theta_{j sd}. \quad (2)$$

In this paper, the shortest path can be chosen by PIAOR. Therefore, the length of the tube can be considered the cost of the Physarum tubular network. The link cost is affected by the location of the next hop node, and we use the projected distance of the node taken as a measure factor. The smaller the projection distance, the closer the candidate node is to the destination node, and the more probable it should be selected as the next hop.

3.2. Coal Mine MANET. The environment in the underground mine is complex and changeable, and there may exist blind wireless coverage areas in the coal mine working face. Miners can construct MANET through smart mobile terminals that they carry to collect data (temperature, humidity, pressure, and gas concentration) in real time, to achieve the safe operation in underground mines. The data collected by miners can be divided into emergency data and non-emergency data. Emergency data has to be transmitted to the ground control center in a timely manner. Non-emergency data can be transmitted by choosing an optimized routing path within the allowed delay time.

As showed in Figure 3, each miner moves within a fixed range of activities, and the communication range of intelligent mobile terminals is limited. Miners can cooperatively transmit the collected data through multiple hops until the wireless access point in the underground mine. The coal mine requires continuous monitoring without interruption, which consumes energy of terminals quickly when receiving and forwarding data. Intelligent terminals carried by miners are powered with limited capacity, which cannot be charged during its using in underground mines and cannot satisfy the need for one working shift. The problem of terminal

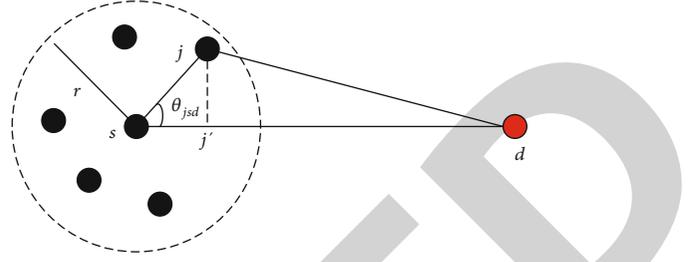


FIGURE 2: Example of one region in coal mine MANET.

energy consumption seriously affects the application of intelligent mobile terminals in coal mine MANET [26, 27]. In the energy consumption of nodes, the calculation of the algorithm consumes less energy, and most of the energy is consumed by data transmission. During the operation of the routing algorithm, the data processing and calculation consumes less energy. However, in data transmission, nodes consume a lot of energy to receive and forward data. Therefore, when selecting the next hop node to transmit data, it is necessary to consider the remaining energy of the node and save and balance the energy consumption by designing an autonomously optimized routing protocol based on the Physarum model.

In coal mine MANET, nodes can obtain the information on the remaining energy of neighbor nodes by locally exchanging “hello” messages in a fixed period. When transmitting data, a node with more residual energy will have more possibility to be selected as the next hop to ensure reliable data transmission.

4. Physarum-Inspired Autonomous Optimized Routing Protocol

4.1. Physarum Model. There is a positive feedback mechanism between the flow and the continuity in the tube network formed by the Physarum itself. The flow in the tube increases, the tube becomes wider, and the continuous increases. At the same time, the wider tube will carry more traffic. Based on this positive feedback mechanism in the Physarum model, the researchers have obtained the mathematical model for Physarum path optimization, which can dynamically adapt to the parameter change of the coal mine MANET. Due to the instability of the coal mine MANET constructed by intelligent mobile terminals, when nodes randomly leave or join the network, the routing path should be reconstructed considering the influence of the remaining energy and cache of the node in the next hop selection.

Since the protoplasm density of each node is different, the pressure at each node is also different. Let P_i and P_j denote the pressure at nodes i and j , respectively. In the Physarum-inspired path-finding model, each tube is a cylinder with a length of $L_{i,j}$ and a radius of $r_{i,j}$. We define the tube from i to j as Tube $\langle i, j \rangle$. The flux in each tube can be expressed by the Poisson equation as

$$Q_{i,j} = \frac{\pi r_{i,j}^4 (P_i - P_j)}{8\eta L_{i,j}} = \frac{D_{i,j} (P_i - P_j)}{L_{i,j}} = \frac{D_{i,j} \Delta P_{i,j}}{L_{i,j}}, \quad (3)$$

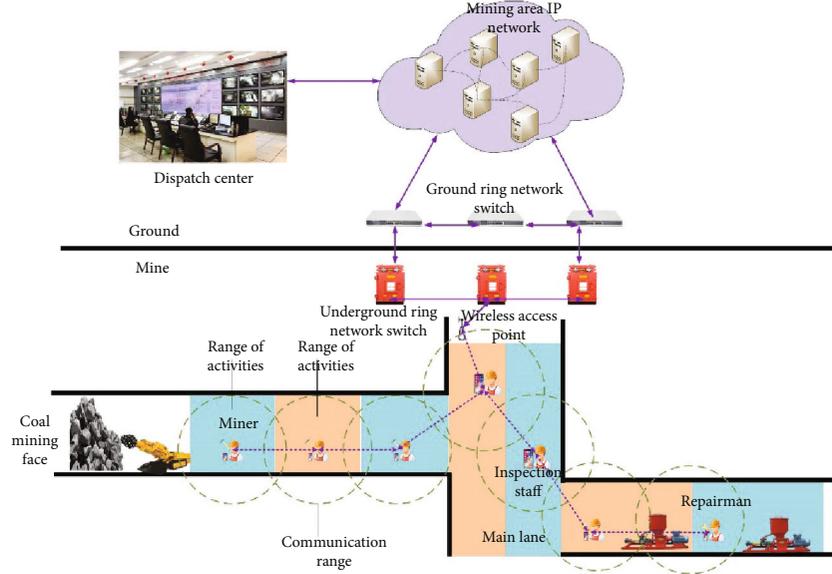


FIGURE 3: Data transmission scenario of blind wireless coverage areas.

where $Q_{i,j}$ represents the flux in Tube $\langle i, j \rangle$. $\Delta P_{i,j} = P_i - P_j$ denotes the pressure difference between link $\langle i, j \rangle$, η denotes the fluid viscosity in tubes, and $D_{i,j} = \pi r_{i,j}^4 / 8\eta$ indicates the conductivity of the tube.

According to formula (3), the flux passing through node i to j in the tubes is determined by $\Delta P_{i,j}$, $L_{i,j}$, and $D_{i,j}$. Assuming that the capacity of each node is 0, according to the principle of flow conservation, the sum of the outflow from the source node is equal to the sum of the inflow to the destination node, and the sum of the inflow to an intermediate node is equal to the sum of the outflow from this node. The traffic of each node can be calculated as follows:

$$\sum_j \frac{D_{i,j}}{L_{i,j}} (P_i - P_j) = \begin{cases} I, & i = s, \\ -I, & i = d, \\ 0, & \text{others,} \end{cases} \quad (4)$$

where I is the outgoing traffic of the source node s and is the incoming traffic for the destination node d . The sum of the traffic of the intermediate nodes is always 0. Because the total amount of fluid in the tube network is constant, there is the competitive relationship among the paths, which will continue for some time. Eventually, an optimized path will come into being that connects all food sources.

The Physarum model can change the flow of each tube to obtain the distributed food sources based on its own adaptability. In the adaptive process, we can optimize the routing protocol through the evolution of $\Delta D_{i,j}(t)$. With the operation of the network, the link status changes with the consumption of node resources and the movement of the node. When selecting the next hop node, the traffic value of the neighbor node will be calculated by conductivity. The self-adaptability of the algorithm makes the conductivity change over time, so the flow value is different in each period of time. In the path optimization model of Physarum, it seeks

food by adjusting its shape and gradually forms an efficient and clear network tube, with the constraint that the total flow in the Physarum keeps constant. Adapting to the adaptive behavior of the tube, the change in conductivity over time can be expressed as

$$\frac{d}{dt} D_{i,j} = f(|Q_{i,j}|) - \gamma D_{i,j}. \quad (5)$$

The discretized form of the above formula is

$$D_{i,j}(n) = (f(|Q_{i,j}|) - \gamma D_{i,j}(n-1))\Delta t + D_{i,j}(n-1), \quad (6)$$

where $\gamma D_{i,j}$ and $f(Q) = ((Q_{i,j}) / \sum_{j=1}^N Q_{i,j})$ represent the shrink rate and the growth rate of the tube, respectively.

$$\Delta t = \frac{1}{\text{PPS}}, \quad (7)$$

where Δt denotes the time granularity of evolution. The value of time granularity is related to the density of forwarding packets (packets per second, PPS). To ensure that the time granularity of evolution is not too large, we set $\max(\Delta t) = 0.1$.

Formula (6) shows the dynamic relationship of conductivity with time. With this formula, we can calculate the conductivity of the tube at the next moment and get the value of the new flow, so as to optimize the data transmission.

4.2. Optimization Model. The Physarum model is derived from hydrodynamics and cannot be directly applied to MANET. In this paper, based on the state of MANET, we reasonably map the parameters in formulas (3) and (5).

4.2.1. Parameter Mapping of the Basic Model. In order to choose a suitable next hop for data transmission, we should consider factors such as node energy, node cache, and link

status in the network. In this paper, three important parameters in formula (3) are modified, such as conductivity $D_{i,j}$, length $L_{i,j}$, and pressure difference $\Delta P_{i,j}$. An autonomous optimized routing protocol for coal mine MANET is designed to select the next hop node.

Since conductivity $D_{i,j}$ is an inherent physical characteristic of the network, we normalize the received power P_j of neighbor node j as the initial value of $D_{i,j}$. P_j denotes the quality of the link, which is also an inherent characteristic of the wireless link.

$$\widehat{D}_{i,j} = \frac{P_j - P_{\min}}{P_{\max} - P_{\min}}, \quad (8)$$

where $\widehat{D}_{i,j}$ represents the normalization of the received signal strength of link $\langle i, j \rangle$, P_{\min} represents the minimum power capable of supporting reliable communication between neighbor nodes, and P_{\max} represents the maximum power for communication between neighbor nodes. The power value of the node is determined by the network chip of the intelligent terminal node.

Corresponding to the length $L_{i,j}$ of the Physarum model, we use the projection distance of the nodes to express the length of the tube. As shown in Figure 2, the physical location of the node can be obtained by positioning device, which can be broadcasted to its neighbors, so that the physical distance between any two nodes and the projection distance relative to the destination node can be calculated. $L_{i,j}$ can be expressed by the following formula:

$$L_{i,j} = \frac{L_j' d}{L_{id}}, \quad (9)$$

where $L_j' d$ is the projection distance of node j relative to the destination node, and L_{id} is the distance between node i and node d .

In hydromechanics, fluids tend to flow to nodes with lower pressures. Similarly, data packets are expected to be relayed through better performing nodes. The multihop transmission characteristics of MANET make the link quality closely related to the performance of the next hop node. If a node has more remaining energy and buffer, it means that it has more capability to route and forward data and has more buffer space to store data packets. In MANET routing, the remaining energy and buffer of nodes are important parameters that should be considered comprehensively when selecting the next hop. The node with more residual energy and buffer should be selected as the next hop preferentially. Therefore, we construct the pressure difference $\Delta P_{i,j}$ of the Physarum model based on the remaining energy E_{res} and the remaining buffer B_{res} , which is shown as follows:

$$\Delta P_{ij} = \alpha E_{\text{res}} + \beta B_{\text{res}}, \quad (10)$$

where $0 \leq \alpha \leq 1$, $0 \leq \beta \leq 1$ and satisfy $\alpha + \beta = 1$.

Equation Formula (3) can be expressed as

$$Q_{i,j} = \frac{\widehat{D}_{i,j}(\alpha E_{\text{res}} + \beta B_{\text{res}})}{L_j' d / L_{id}}. \quad (11)$$

After parameter mapping and calculation of flux, the neighbor node with the largest value of flux will be selected as the next hop node. The residual energy, buffer, and location of nodes change with the network operation. In order to adapt to this change, evolutionary equations are introduced in this paper. In the initial stage of the network, the conductivity is defined as the received power of neighbor nodes. The conductivity of the next stage is calculated by formula (6). The flux value of the next stage is recalculated by formula (11), and the node with more value of flux $Q_{i,j}$ is selected to transmit data.

4.2.2. Parameter Mapping of the Optimization Process. The definition of the tube shrinking rate γ will affect the calculation of the conductivity over time. The buffer occupation of the nodes is affected by the network status. Excessive data packets stored in one node will cause congestion, which will reduce throughput, increase transmission delay, and deteriorate the network performance. The mobility of terminals in coal mine MANET will affect the reliability of links among neighbor nodes. The more reliable the links are, the better the data transmission will be. Therefore, the shrinking rate of the tube is related to the congestion and link stability of the next hop node. The larger the buffer space is occupied, the more unstable the link caused by node movement, and the easier the tube will shrink. We denote the shrinking rate γ of the tube as

$$\gamma = C_B \times l, \quad (12)$$

where C_B represents the congestion probability and l represents the fracture probability of communication link.

When receiving data, the node will store it in its buffer queue and select the next hop according to the calculated flux. If a node continuously receives data packets, network congestion may occur, and then, data transmission will be deteriorated. Therefore, the link quality and the buffer occupation should be predicted and be used to calculate the shrinking rate. The congestion probability C_B of the potential next hop is defined as

$$C_B = \frac{B_{\text{jitter}} \times B_{\text{avg}}}{0.5},$$

$$B_{\text{jitter}} = \sqrt{\frac{1}{N} \sum_{i=1}^N (B_i - B_{\text{avg}})^2}, \quad (13)$$

$$B_{\text{avg}} = \frac{1}{N} \sum_{i=1}^N B_i,$$

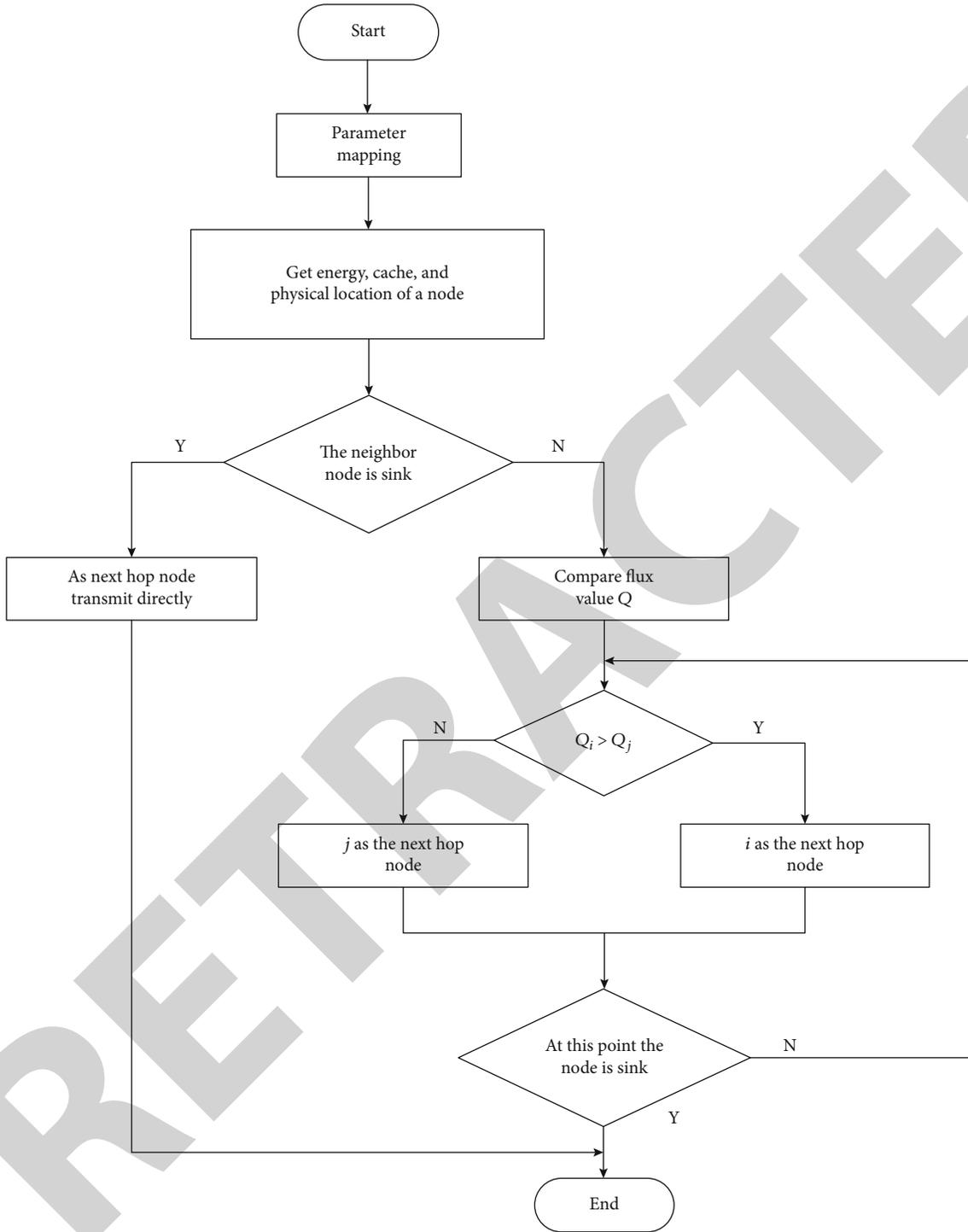


FIGURE 4: Flow chart of PIAOR.

where B_{jitter} represents the buffer occupation jitter and B_{avg} is the average cache. N denotes the count of buffer occupation in Δt , and B_i denotes i th buffer occupation.

In order to achieve efficient data transmission, the buffer occupation of the node should be considered when selecting the next hop. B_{jitter} can be set as a penalty factor to reduce the probability that the node with excessive buffer occupation

and large jitter to be selected as the next hop. The smaller the average buffer occupation, the smaller the penalty factor B_{jitter} , the less the congestion probability, and the more priority of this node should be selected as the next hop.

As the movement of terminals in coal mine MANET may cause the disconnection of links, the nodes need to reconstruct the routing path, which will increase the delay of data

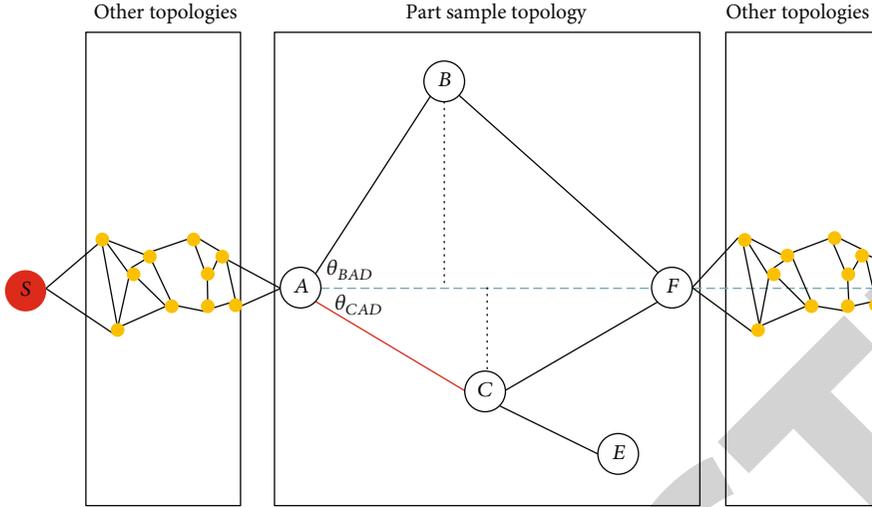


FIGURE 5: Routing decision of node A in network initial stage.

transmission. In this paper, we measure the link availability by the link connection time and consider the link quality in routing decisions.

When nodes move, the nodes may be close to each other or away from each other, with 50% probability, the following formula can be used to represent the probability model of link availability prediction

$$l(T_p) = (1 - e^{-2\lambda T_p}) \left(\frac{1}{2\lambda T_p} + \varepsilon \right) + \frac{\lambda T_p e^{-2\lambda T_p}}{2}, \quad (14)$$

where λ represents the terminal mobility, T_p represents the time interval to predict the link availability, and $l(T_p)$ represents the fracture probability of communication link from the initial time t_0 to $t_0 + T_p$. The value of ε is determined by environmental factors, which change with time and mobility and cannot be calculated by an accurate mathematical formula.

In order to adapt to the dynamic changes of environmental factors, it is more practical to predict the value of ε . Within the time interval (T_p), $T_{r,i}$ ($i=1\dots n$) represents the link's available time slice. The probability that the link can be continuously available for each time interval can be expressed as

$$l_m(T_p) = (1/n) \sum_{i=1}^n (T_{r,i}/T_p). \quad (15)$$

In formula (14), replacing $l(T_p)$ with $l_m(T_p)$, we can get

$$\varepsilon_m = \frac{l_m(T_p) - (1/2)\lambda T_p e^{-2\lambda T_p}}{1 - e^{-2\lambda T_p}} - \frac{1}{2\lambda T_p}. \quad (16)$$

TABLE 1: Route decision of node A.

Path	D	L_{next}	L_d	θ	B (%)	E (%)	α	β	Q
$A \rightarrow B$	0.7	100	500	60°	1	1	0.62	0.38	0.78
$A \rightarrow C$	0.7	100	500	30°	1	1	0.62	0.38	0.85

A series of ε_m can be obtained by the above operation according to the corresponding T_p , and then, ε can be predicted by the following formula:

$$\varepsilon \approx (1/n) \sum_{i=1}^n \varepsilon_{m,i}. \quad (17)$$

The available time of link is predictively calculated by instant information of the network, considering the dynamic characteristics of the link, which will truly reflect the link reliability and improve routing performance.

5. Routing Decision

5.1. Routing Decision Process. The topology of coal mine MANET will change dynamically with the moving of miners carrying the smart terminals. The PIAOR algorithm can improve the rationality of routing decision and achieve the optimal path construction considering multiple network parameters, based on current and historical information. The routing decision processes and its flow chart is shown as follows:

Step 1. Calculate the flux value at the beginning of network operation through formula (3), $D_{i,j}$ and $\Delta P_{i,j}$ are calculated according to formulas (8) and (10), respectively. $L_{i,j}$ is calculated by formula (9).

Step 2. After the network has been running for some time, the performance parameters and the network state change.

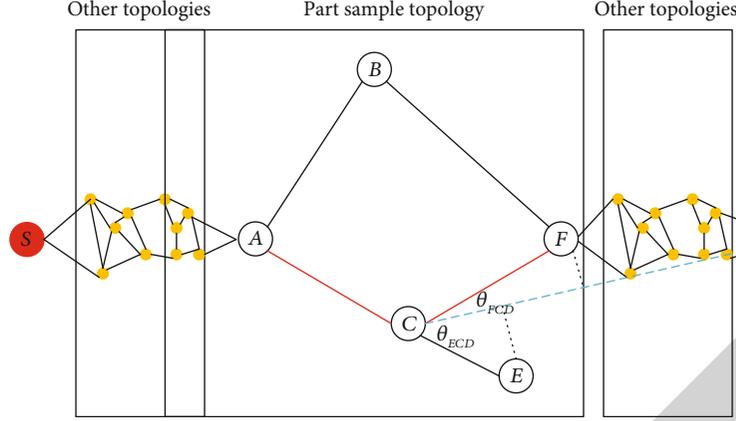


FIGURE 6: Routing decision of node C in network initial stage.

Route optimization is carried out by adaptive link state quality adjustment and adaptive parameter adjustment strategy. Conductivity D can be recalculated by the differential evolution equation of Physarum (5), and the flow value Q of the next stage can be calculated by formula (10). The node with the largest Q is selected as the next hop node.

Step 3. Repeat the above process until data packets arrive at the destination node.

The main flow chart of PIAOR is shown in Figure 4.

5.2. Routing Decision Analysis. For a more detailed introduction of PIAOR, one part of the network is selected as an example to analyze routing decisions. In PIAOR, multiple network parameters such as energy, buffer, and mobility of nodes are comprehensively considered when making routing decisions. By calculating the flux in the tube, the node with the largest flux will be selected as the next hop to transmit data packets. Suppose the distance between the current node and the next hop node is $L_{next}(m)$ and the distance from the destination node is $L_d(m)$.

5.2.1. Network Initial Stage. In the following routing decision analysis, we assume one part of network topology shown in Figure 5. Node S is the source node, node D is the destination node, and node A is the current node, which has stored data packets and need to send to the destination node. Nodes B and C are the neighbors of node A .

In the network initial stage, the node has consumed less energy and has used less buffer. The conductivity of the link is calculated by formula (8). Node A selects the one with a large flux value from neighbor nodes B and C as the next hop transmission node. According to the autonomous optimized routing model, a calculation table for selecting the next hop in the initial stage is shown in Table 1.

From Table 1, compared by the flux in tube (Q), the projection distance of node C is small, with larger QA , $C = 0.85$, so node C is selected as the next hop.

After node C has received the data packets, as shown in Figure 6, it will start the routing decision process and select

TABLE 2: Route decision of node C.

Path	D	L_{next}	L_d	θ	B (%)	E (%)	α	β	Q
$C \rightarrow F$	0.7	100	450	15°	1	1	0.62	0.38	0.89
$C \rightarrow E$	0.8	50	450	50°	1	1	0.62	0.38	0.86

the next hop from its neighbors (node E and node F), which is shown in Table 2.

As seen from the above table, compared by the flux in tube (Q), node C chooses node F with a larger value of Q as the next hop node.

5.2.2. Network Operation Phase. Evolution follows the transmission of data over the network. Suppose that after the network runs for a period of time, the location, energy, cache, and distance of nodes all change. The following figure shows the routing decision process after the network state changes.

As shown in Figure 7, after the network runs for a period of time, the network topology changes, and the node's energy and cache usage also change. Node A needs to recalculate the traffic value Q when forwarding data. The evolution calculation process is shown in Table 3.

The new conductivity obtained after the evolution of the above table can be used to obtain new flow values. The calculation is shown in Table 4.

According to Table 4, the conductivity, residual energy, and residual cache all changes; the factors of pressure difference ΔP and node projection distance L are considered synthetically, compared by the flux in tube (Q), with larger QA , $B = 0.64$, so node B is selected as the next hop.

When node B selects the next hop to send data, because node B 's neighbors are only A and F , node B chooses node F as the next hop, as shown in Figure 8.

When the network is running, data is sent from the source node S to the destination node D , and the routing selection is completed in turn as described above. The PIAOR algorithm can achieve load balancing and energy

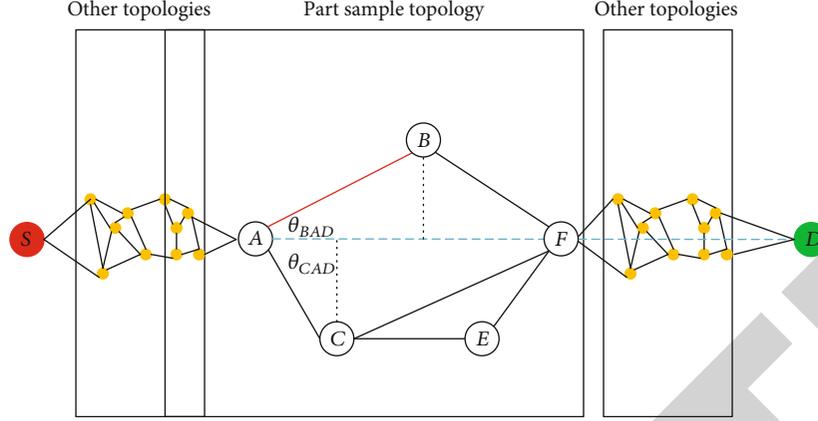


FIGURE 7: Decision example of node A after network state changes.

TABLE 3: Evolution of node A.

Path	$D(n-1)$	C_B	l	γ	$f(Q)$	Δt	$D(n)$
$A \rightarrow B$	0.7	100	500	30°	0.9	0.9	0.62
$A \rightarrow C$	0.73	50	500	60°	0.6	0.5	0.62

TABLE 4: Route decision of node A after evolution.

Path	D	L_{next}	L_d	θ	B (%)	E (%)	α	β	Q
$A \rightarrow B$	0.7	100	500	30°	0.9	0.9	0.62	0.38	0.64
$A \rightarrow C$	0.73	50	500	60°	0.6	0.5	0.62	0.38	0.35

balancing and extend the network survival time and is of great significance for the uninterrupted data collection and transmission in coal mines.

6. Simulation Experiment

6.1. Simulation Environment and Experimental Parameters. Based on the NS2 simulation platform, the performance of PIAOR has been tested and the results such as delivery ratio, end-to-end delay, throughput, and network lifetime were compared to those of PIMAR, GPSR, and P-IRP. The performance indicators are defined as follows:

Delivery Ratio. The delivery ratio is the ratio of CBR packets arriving at the gateway node to the total packets sent by source nodes. The delivery ratio can be defined as follows:

$$\text{Delivery ratio} = \frac{\text{Packets received by gateway}}{\text{All packets}}. \quad (18)$$

End-to-End Delay. The average value of constant bitrate (CBR) packets delays from each source node to

the gateway node. The average end-to-end delay can be defined as follows:

$$\text{Delay} = \frac{\sum_i^I \text{CBR}(i)}{I}, \quad (19)$$

where $\text{CBR}(i)$ is the delay of packet i and I is the number of packets in an experimental process.

Throughput. Throughput is the amount of data received by the gateway node in one second.

Network Lifetime. The time when the first node dies due to energy exhaustion is defined as the network lifetime.

The parameters of the simulation network are listed in Table 5.

In the simulation, we set the network in a long and narrow area of $1000 \times 8 \text{ m}^2$ to simulate the tunnel in an underground mine. The terminals in the underground mine are mostly carried by miners, inspectors, or other mobile devices, and their movement range and trajectory have certain rules. The areas covered by miners of different professions are limited. To simulate real scenarios, the network area is divided into multiple subregions of $200 \times 8 \text{ m}^2$. 100 nodes are randomly deployed in subregions and move randomly within the subregion. A gateway node is deployed at one end of the network.

6.2. Performance Analysis

6.2.1. Delivery Ratio. The trends of delivery ratio for four different protocols are shown in Figure 9. PIAOR has the highest delivery ratio, followed by P-IRP and GPSR, and PIMAR has the lowest one. PIMAR does not consider the movement of nodes. If the speed of the movement is high, the update delay of the node depth may cause poor network performance due to growth of routing paths. GPSR and P-IRP only use the current location of nodes and have no prediction on the trend of node movement. When the nodes move fast, the possibility of link breakage will increase and the delivery ratio will decrease. PIAOR uses the projection distance of the nodes relative to the gateway to map the length of the tube in

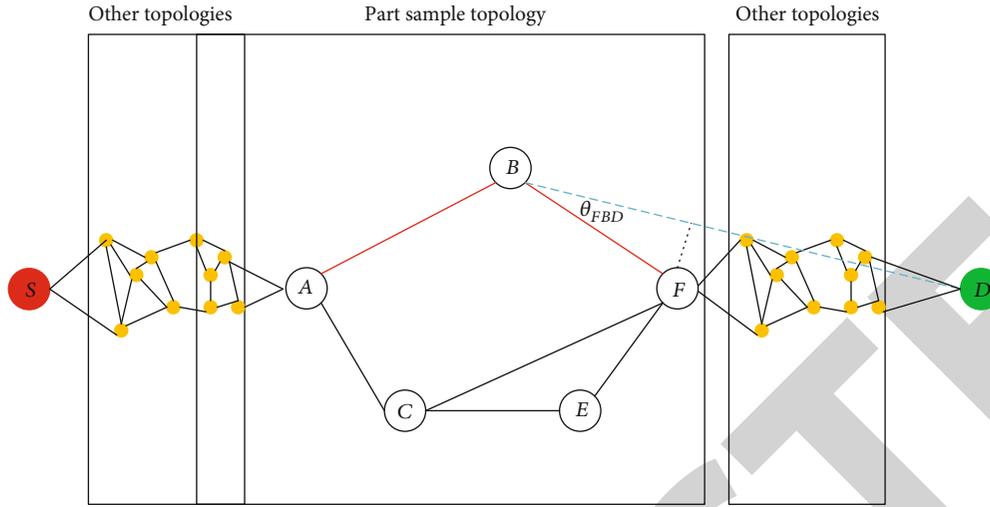
FIGURE 8: Decision example of node B after network state changes.

TABLE 5: Simulation parameters.

Topography size	$1000 \times 8 \text{ m}^2$
Divided area	$200 \times 8 \text{ m}^2$
Simulation time	3000 s
Transfer range	50 m
Traffic type	CBR
Packet size of CBR	64 B
Data flow rate	0.3 MB/S
Number of CBR flows	20
Terminals	100
Gateways	1
Nodes mobility model	Random waypoint model

the Physarum network, so as to ensure the convergence direction of the route. PIAOR utilize the motion prediction model to predict the link instability, which can effectively avoid selecting unstable links and improves network delivery ratio.

6.2.2. End-to-End Delay. In Figure 10, PIMAR has the highest latency, followed by P-IRP and GPSR, and PIAOR has the lowest. Because PIMAR does not support routing under high-speed node movements, routing decisions are inefficient at high-node movement speed, resulting in node data packet backlogs and path growth, increasing latency. The criteria used by GPSR and P-IRP to evaluate the next-hop node are too simple to make a good prediction of the changes in link quality. In high-speed conditions, there are more unstable links, so the end-to-end delay is higher. The node motion prediction strategy of PIAOR can effectively reduce the possibility of selecting unstable link, reduce the backlogs caused by routing failure of packets, and reduce the delay.

6.2.3. Throughput. Figure 11 shows the trend of the throughput of four network protocols with an increasing speed. PIMAR's throughput is higher in the environment of low-speed movement of the node, but the performance degradation is large at a high speed. GPSR and P-IRP have better throughput performance than PIMAR, and PIAOR has the best throughput. PIAOR can effectively predict unstable links and can optimize link selection based on current and historical information. It can more comprehensively measure link quality and improve throughput performance.

6.2.4. Network Lifetime. In Figure 12, PIAOR has the highest network lifetime and GPSR has the lowest network lifetime. The definition of the network survival time is the time when the number of network node death accounts for 80% of the total number of nodes. At this time, the remaining nodes are less than 20 and the network will not be able to provide normal communication support. PIMAR's parameter adaptive adjustment strategy can effectively achieve network load balancing and energy balancing when the node's movement speed is low, and the network survival time is longer. However, in high-speed environments, PIMAR's routing decision method is prone to routing loops due to the delayed updating of node depth information, resulting in a longer data packet transmission path and increased energy consumption. GPSR does not consider energy factors and may overuse low-energy nodes, causing them to die prematurely and affecting network lifetime. P-IRP takes energy into consideration and therefore has a longer network lifetime. PIAOR considers the energy and cache of the next hop node, and there is no problem of telling the environment that the routing path becomes longer, which can effectively reduce the use of nodes with lower energy and larger loads. In addition, because PIAOR can continuously optimize the accuracy of link state evaluation, avoid choosing problematic links, thereby extending network survival time.

From the above experimental analysis, it can be obtained that the PIAOR algorithm is superior in the delivery ratio,

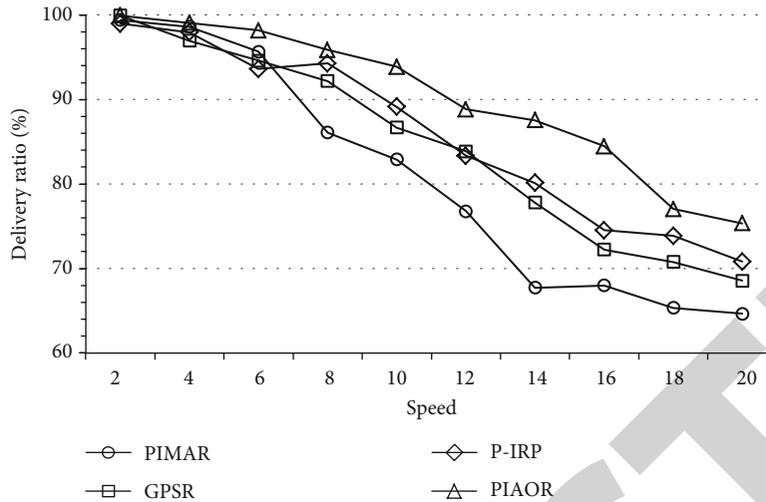


FIGURE 9: Delivery ratio.

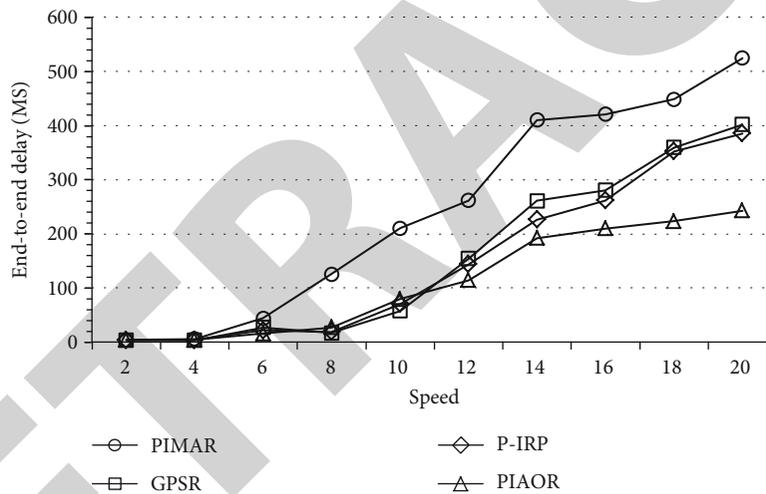


FIGURE 10: End-to-end delay.

end-to-end delay, throughput, and network lifetime performance and is suitable for the underground environment to ensure the stable and efficient transmission of data in the coal mines.

7. Conclusions

In this paper, we propose a bionic algorithm PIAOR. The PIAOR algorithm comprehensively considers the energy and cache of nodes, as well as the link status, and introduces the node's movement model to calculate network flux, which is used to measure the quality of the link, so as to achieve reliable and efficient data transmission. In order to adapt to the changes in network topology caused by the movement of underground nodes, we introduce the differential evolution equation of the Physarum model to

predict the congestion and availability of the link, which is used to calculate the conductivity among neighbors and recalculate the flow value to find an optimal path for data transmission. Based on analyzing the variation of energy and link quality with node depth, the parameter adaptive strategy and communication link autonomous optimization strategy is proposed. PIAOR uses local information to calculate the regional flow to make routing decisions, which has greatly reduced the complexity of the algorithm, lowered the network overhead, and improved the scalability. Through theoretical analysis and NS2 simulation experiments, the result shows that PIAOR is superior to other similar protocols in terms of throughput, average end-to-end delay, network lifetime, and delivery ratio. PIAOR has achieved energy and load balance and has extended the life cycle of the network.

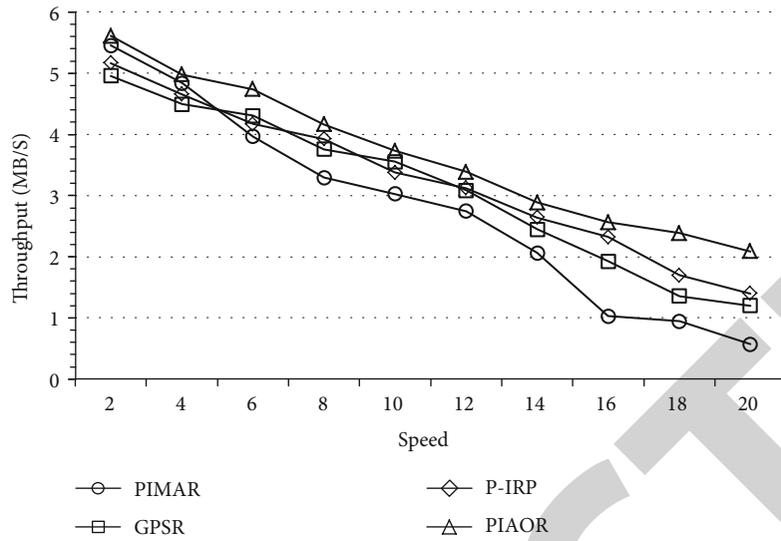


FIGURE 11: Throughput.

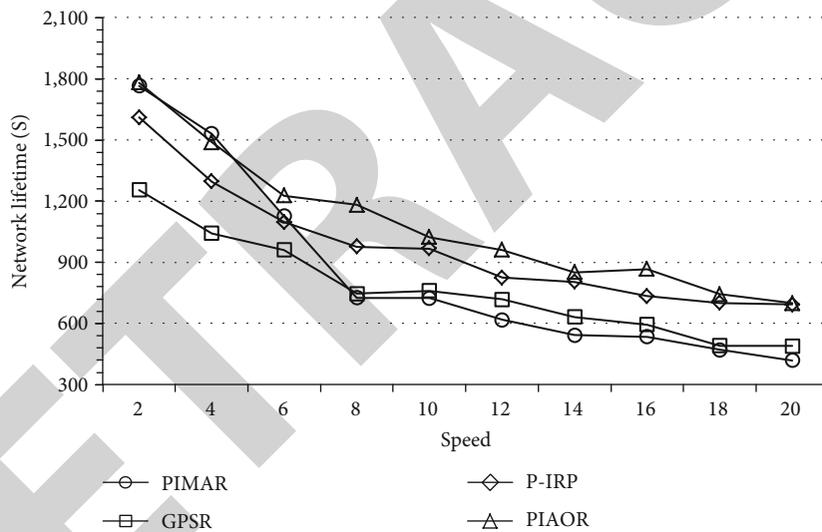


FIGURE 12: Network lifetime.

In future work, faced with the limited energy of the nodes in coal mine MANET, an energy optimized routing algorithm can be designed to reduce the energy consumption for data transmission. According to the activity characteristics of nodes in an underground mine, different mobility models can be established, so as to further study its impact on network performance. In addition, combining Physarum models with other intelligent algorithms to solve more complex network optimization problems is another direction of our future research.

Data Availability

The simulation experiment data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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