A Packet Forwarding Protocol in Coal Mine Opportunistic Networks

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Abstract —A packet forwarding protocol based on terminals' Markov mobility model (TMM) is proposed for coal mine poor connectivity in opportunistic networks since its complex environment. First, a Markov model is established for predicting the probability of terminals' encounter. Then the network-delay in the condition of next selected relay-terminal (NDT), the probability of terminal encounter with destination (PTD) and the terminal diffusion range (TDR) are calculated based on the model, by which the best relay-terminal can be obtained to receive data packet based on Analytic Hierarchy Process (AHP). Theoretical analysis and simulation results show that the proposed protocol has a better performance in terms of delay and overhead compared with Flooding and HMPR method, and it's more suitable for coal mine opportunistic networks.

Index Terms—Packet forwarding protocol; opportunistic networks; Markov model; terminal attribute; coal mine

I. Introduction

The current communication technologies in coal mine, such as Wi-Fi, Zigbee and RFID, may result in network blind spots where base stations inconvenient to install, such as the curved tunnel [1]. Opportunistic Network [2] is one kind of challenged networks, which focus on the feature that there doesn't exist a persistent path between the source and the destination. The terminals of opportunistic network exploit the meeting opportunities with others to transmit messages. The method can be used to solve the problem of network coverage in the coal mine without a complete communication link.

The current study focused on opportunistic networks routing algorithm has considered the impact of terminals' historical utility [3], [4]. Liu Qilie *et al*. proposed a routing algorithm in opportunistic network based on historical utility [5], which takes into account both the frequency of terminals' contact and the contact time for packet transmission to ensure that the packets' forwarding path from source terminal to destination is best and the algorithm has an advantage in packet delivery ratio. However, this algorithm only considers the terminals' relationship with destination. As for the limited range of terminals' movement in the coal mine and the limited kinds of miners which can contact with destination, the packet usually transfer to destination by more than one hop. So the algorithm which considers terminals' relationship with destination is not enough in coal mine opportunistic networks.

Aiming at the problem that the current routing protocols in opportunistic networks rely on simple mobility models, and rarely consider social characteristics [6], Cheng Gang *et al*. [7] put forward a routing protocol which brings an adapted discrete Markov chain into nodes' mobility model and calculates the transition probability between successive statuses.

Niu Jianwei *et al*. propose a social network model based on Markov model in [8], where a terminal move among different Main-scenarios (places frequently visited by terminals) according to the Markov rule, and two different terminals in the same Main-scenario can establish a connection with a certain probability. Then the paper analyzes the performance of copy limited flooding over opportunistic networks, where each node can only send no more than k copies of the same packet in terms of delivery rate and delay.

Many recent studies based on social Morkov mobility model take into account the terminals' movement rule, time changes and other factors [9], and terminals in this model can move to any scenario in society [10], [11]. However, the range of terminals' movement are limited in coal mine and the different kinds of miners correspond to different movement range. So it's necessary to establish a new terminal mobility model of coal mine and propose a new packet forwarding protocol for coal mine opportunistic networks.

In this paper, we aim at proposing a new packet forwarding protocol to solve the problem of poor connectivity in coal mine opportunistic networks. First, a Markov model is established for predicting the probability of terminals' encounter. Then NDT, PTD, TDR are calculated based on the model, by which the best relay-terminal can be obtained to receive data packet based on AHP.

The remainder of the paper is organized as follows. Section II describes a terminals' Markov mobility model and calculates terminals' attribute data based on the model. In Section III, we give the specific process of relay-terminal selection based on AHP. Section IV compared the performance with the Floding and HMPR method. Finally, the paper is concluded in Section V.

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II. Calculation of Terminal Attribute Data

The miners in coal mine are divided into different kinds according to their different nature of work, such as monitor, tester, fitter, maintenance and blaster. Ranges of Miners' movement in coal mine are different during their working hours, and terminals (miners who carry communication device) also have different mobility in workplace. For example, the monitor can move at the entire tunnel during his working time, but blasters' mobility is limited since that they only working at the end position of the tunnel, fitters can also move within the range of their workplace according to the nature of their work. Fig. 1 shows the spatial distribution of different kinds of miners. Different kinds encounter in their overlap workplace, and miners with same kind encounter in their own workplace. Different kinds of miners work independently, which lead to poor network connectivity.

In this paper, packet transmission in opportunistic network adopts the "store-carry-forward" paradigm by leveraging the mobility of terminals, and the ultimate goal is to forwarding packet to the destination (AP) in the coal mine.

Terminals' mobility plays an important role in affecting the performance of forwarding protocol in coal mine opportunistic networks, furthermore, the trajectory of terminals' movement is driven by terminals' characteristics. Therefore a Markov model is established to predict terminals' mobility and encounter probability. Based on the model, terminals' attributes can be calculated and the network delay and overhead can be optimized by choosing the best terminal as the relay-terminal to receive packet.

A. Model of Terminals

The whole workplace in coal mine were divided into N scenarios, which recorded as $C_i, i = 1, 2 \ldots \mathrm{N}$ respectively, C_D is the position of destination. Statistic the number of terminals' appear time at all scenarios and their movement status, then establish the terminal mobility model based on the statistical results.

At the start time, terminals randomly distribute in either scenario. After that, they can choose to stay for some time or move to other scenario with a certain probability, which related to their own movement rule, and the value finally making up the unit moving probability matrix as follows which exhibits the moving probability of terminals in unit time.

$$L(1) = \begin{pmatrix} p_{C_1,C_1} & p_{C_1,C_2} & \cdots & p_{C_1,C_N} & p_{C_1,C_D} \\ p_{C_2,C_1} & p_{C_2,C_2} & \cdots & p_{C_2,C_N} & p_{C_2,C_D} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{C_N,C_1} & p_{C_N,C_2} & \cdots & p_{C_N,C_N} & p_{C_N,C_D} \\ p_{C_D,C_1} & p_{C_D,C_2} & \cdots & p_{C_D,C_N} & p_{C_D,C_D} \end{pmatrix}_{(N+1)\times(N+1)} \quad (1)$$

where $j \in \{1, 2 \ldots \mathrm{N}\}$, p_{C_i,C_j} is the probability of terminal moving from C_i to C_j in unit time. $p_{C_i,C_j} \neq 0$ indicate that the terminal can move between C_i and C_j scenarios. $p_{C_i,C_j} = 0$ indicate that the terminal cannot move between the two scenarios. If $i = j$, p_{C_i,C_j} indicate that the probability of retention in C_i per unit time of the terminal.

Define active terminal as the terminals which can move to any scenarios in workplace, and the movement speed exceed 0.5m/s, Fig. 2 shows the moving state diagram of active terminal.

In Fig. 2, terminals can move to either adjacent scenarios, and the probability of terminals' presences in each scenario may be different since the difference of terminals' work nature.

Define an-active terminal as the terminals which the movement range within three scenarios and the speed less than 0.5m/s. Terminals of this kind has limited movement range and poor ability of packet forwarding. Fig. 3 shows the moving state diagram of an-active terminal.

Define Semi-active as the terminals not belong to any of the above two cases. Fig. 4 shows the moving state diagram of terminal U .

Where $i \in 1, 2 \ldots \mathrm{N}$ and $i < j < N + 1$ in the diagram. Different kinds of terminals have different movement range, corresponding to different i and j.

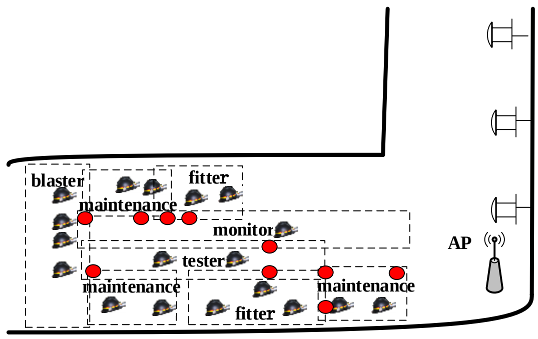

Fig. 1. Spatial distribution of different kinds of miners

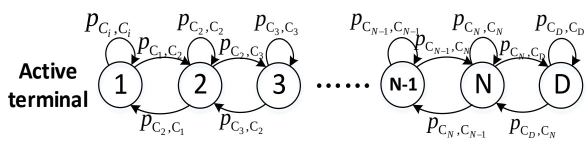

Fig. 2. Moving state diagram of active terminals

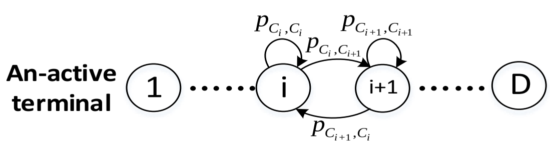

Fig. 3. Moving state diagram of an-active terminals

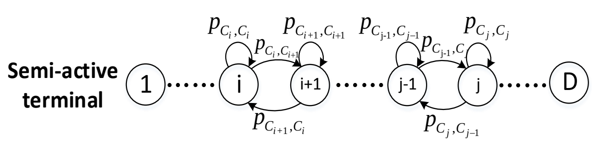

Fig. 4. Moving state diagram of semi-active terminals

The Matrix below indicates the probability of terminals' possible position after k units time.

$$L(\mathrm{k})=\begin{pmatrix} p_{C_1,C_1} & p_{C_1,C_2} & \cdots & p_{C_1,C_N} & p_{C_1,C_D} \\ p_{C_2,C_1} & p_{C_2,C_2} & \cdots & p_{C_2,C_N} & p_{C_2,C_D} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{C_N,C_1} & p_{C_N,C_2} & \cdots & p_{C_N,C_N} & p_{C_N,C_D} \\ p_{C_D,C_1} & p_{C_D,C_2} & \cdots & p_{C_D,C_N} & p_{C_D,C_D} \end{pmatrix}^k_{(N+1)\times(N+1)} \tag{2}$$

where L_{C_i,C_j} Indicates the probability of terminal moving from C_i to C_j after k units time, note as:

$$L_{C_i,C_j}(k)=P(X_k=C_j \mid X_0=C_i) \tag{3}$$

The terminal a is position in C_i at time k_a, and the terminal b is position in C_j at time k_b. The probability of two terminals encounter in C_r at time k is:

$$F_{ab}^{C_r}(k)=L_{C_i,C_r}^{a}(k-k_a)L_{C_j,C_r}^{b}(k-k_b) \tag{4}$$

At time k, the probability of a,b encounter in any scenario is:

$$F_{ab}(k)=\sum_{r=1}^{N}F_{ab}^{C_r}(k) \tag{5}$$

B. Calculation of Terminal Attribute Data

In the selection of relay-terminal, NDT、PTD、TDR are important considerations. These three important attributes data can be calculated based on the Markov model, and the specific calculation method are detailed as follows:

1). Network-delay in the condition of next selected relay-terminal (NDT).

Selecting different terminals as the next relay-terminal results in different network-delays, this delay can be obtained based on terminals' movement rule, which include the time of source terminal's moving, time of source terminals' residence in scenarios, time of packet forwarding and the time of relay-terminals' store-carry-forward process until message arrive AP. As an important factor, the data of NDT decides whether the packet forwards or not. The method for obtaining NDT is divided into two steps.

a) According to the Markov model, terminal may choose to stay for a period of time or move to other scenarios when it appears in C_i. k_z and t_z express the packet forwarding probability and the average packet forwarding time , respectively when terminals encounter. k_d and t_d express the probability of terminal retention in the scenario and the length of time retention here respectively.

Accumulation of previous M times forwarding time is:

$$Z_M=\sum_{q=1}^{M}t_q \tag{6}$$

Average forwarding time is:

$$t_z=\frac{Z_M}{M} \tag{7}$$

Assuming that the total number of terminals in coal mine were m, respectively noted as 1,2 ... m, the probability of packet forwarding for terminal a in C_r is:

$$k_z=\sum_{b=1}^{m}F_{ab}^{C_r}(k)\times p(f(x_a)<f(x_b)) \quad b\neq a, a、b\in\{1,2...m\} \tag{8}$$

The average retention time of terminal in C_r is:

$$k_d(C_r)\times t_d(C_r)=\sum_{k=1}^{u}\sum_{i=1}^{n}L_{C_i,C_r}\times(p_{C_r,C_r})^k\times k \tag{9}$$

where k means the time retention in C_r, and its maximum value is u.

b) NDT's calculation.

According to the above model, the probability of terminals' encounter in any scenario per unit time can be obtained:

$$p_{a,b}=F_{ab}(1)=\sum_{r=1}^{N}F_{ab}^{C_r}(1) \tag{10}$$

where N is the total scenarios in the coal mine.

The probability of any two terminals encounter per unit time in any scenario is shown in the following matrix, different miners corresponding to different encounter probability:

$$\mathrm{Y}(1)=\begin{pmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,m} & p_{1,D} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,m} & p_{2,D} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{m,1} & p_{m,2} & \cdots & p_{m,m} & p_{m,D} \\ p_{D,1} & p_{D,2} & \cdots & p_{D,m} & p_{D,D} \end{pmatrix}_{(\mathrm{m}+1)\times(\mathrm{m}+1)} \tag{11}$$

The source terminal (terminal 1) carries packet, and the probability of packet forwarding to AP directly through one hop is:

$$p(s=1)=p_{1,D} \tag{12}$$

The probability of packet forwarding to AP after two hops is:

$$p(s=2)=\sum_{a\neq 1}\frac{1}{m-1}p_{1,\mathrm{a}}p_{\mathrm{a},D}, a\in\{1,2,...,m\} \tag{13}$$

The probability of packet forwarding to AP after h (h is valid hop from the source terminal to AP) hops is:

$$p(s=h)=(\sum_{a\neq 1}\frac{1}{m-1}p_{1,\mathrm{a}})(\sum_{b\neq 1,\mathrm{a}}\frac{1}{m-2}p_{\mathrm{a,b}})...(\sum_{c\neq 1,\mathrm{a,b...}}\frac{1}{m-h}p_{\mathrm{c,D}}), \mathrm{a}、\mathrm{b}...\mathrm{c}\in\{1,2,...,m\} \tag{14}$$

where n is the average number of hops packet forwarding from source terminal to AP, then:

$$n=\sum_{q=1}^{h}q\times p(s=q) \tag{15}$$

Suppose d as the terminal Communication range, s is the distance from source terminal to AP, N_C is the total number of scenarios in the model (For calculation simplicity, define the distance between two adjacent scenarios as d), the average speed of terminal is v.

By the a) analysis, terminal average length of time retention in any scenario is:

$$\overline{t_d} = \frac{\sum_{r=1}^{N_C} k_d(C_r) \times t_d(C_r)}{N_C} \tag{16}$$

If the packet arrives to AP after one hop, delay of terminal forwarding is:

$$t_1 = \frac{l}{v} - k_z(\frac{d}{v} - t_z) + N_C \overline{t_d} \tag{17}$$

The packet forward to AP after average n hops, and the data of NDT is:

$$t_n = \frac{l}{v} - nk_z(\frac{d}{v} - t_z) + (N_C - n)k_d \overline{t_d} \tag{18}$$

2). The probability of terminal encounter with destination (PTD).

Define p as the encounter probability of the terminal and AP. The ultimate goal for the network is to forward the packet to AP, so the probability of terminal encounter with AP is one of the important factors to decide whether to forward the packet or not.

The probability of terminal moving from C_i to C_j can be obtained according to the terminal mobility model:

$$p_{ij} = \sum_{k=1}^{h} L_{C_i, C_j}(k) \tag{19}$$

The probability of terminal moving to C_j from any scenario is:

$$p_{CC_j} = \sum_{i=1}^{N_C} \sum_{k=1}^{h} \frac{1}{N_C} L_{C_i, C_j}(k) \tag{20}$$

The probability of terminal encounter with AP is:

$$p = \sum_{i=1}^{N_C} \sum_{k=1}^{h} \frac{1}{N_C} L_{C_i, C_D}(k) \tag{21}$$

3). Terminal diffusion range (TDR).

The diffusion range of a terminal is the ratio of reached scenarios' number to the total number of scenarios, which reflects the contact condition of terminal to other kinds. The more kinds can be contacted, the higher probability to encounter better terminal for packet forwarding.

In the unit moving probability matrix, the elements in diagonal reflect the circumstance of terminal appearance in each scenario. Terminal diffusion range is the ratio of the number of non-zero diagonal elements to the total number of diagonal elements in the matrix, which notes as:

$$e = \frac{\text{the number of non} - \text{zero diagonal elements}}{\text{the total number of diagonal elements}} \tag{22}$$

III. Relay-Terminal Selection Based on Analytic Hierarchy Process

The algorithm of relay-terminal selection is a typical multi-objective decision algorithm that takes into account many aspects of factors, and makes the most reasonable target terminal selection decisions [12], [13]. The prediction function $f(\mathrm{x}_a), \mathrm{a} \in \{1, 2, ..., m\}$ represents relay-terminal selection cost. The NDT mentioned above is cost attribute, the PTD and TDR are income-producing attributes.

This paper uses AHP to select a relay-terminal, and the specific select process are detailed as the following sequence:

A. Establish the Hierarchical Structure

Establish the hierarchical structure for terminal selection as shown in Fig. 5.

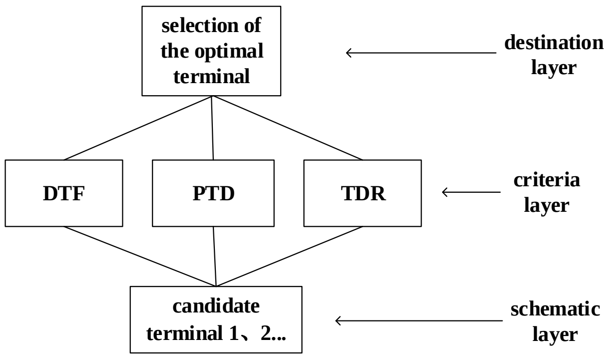

Fig. 5. Hierarchical structure for terminal selection

B. Define the Attribute Relative Importance Matrix.

Define the attribute relative importance and then form a matrix.

Note that the judgment matrix is $Q = (\mathrm{q_{aj}})_{\mathrm{n \times n}}$, which has the following characteristics:

$$\begin{cases} q_{aj} > 0 \\ q_{aj} = 1/q_{ja} \\ q_{aa} = 1 \end{cases} \tag{23}$$

Construct the matrix according to the 1-9 scale method to express the relative importance of the terminal attributes.

$$\begin{array}{c} \begin{array}{ccc} \textbf{DTF} & \textbf{PDF} & \textbf{TDR} \end{array} \\ \begin{bmatrix} 1 & 2 & 5 \\ 1/2 & 1 & 5 \\ 1/5 & 1/5 & 1 \end{bmatrix} \end{array} \tag{24}$$

C. Weight Calculation and Consistency Check

From $QW = \lambda W$, $\lambda = 3.0536$ can be obtained. Normalize the maximum characteristic vector W to get the target weight vector: $\alpha = (0.5031, 0.4088, 0.0880)$.

Note $y_j^{\max}$ 、 $y_j^{\min}$ as the Maximum and minimum dates of the terminal attributes j respectively. The jth attribute of terminal a is expressed as y_{aj}. For cost attribute, delay of terminal forwarding, the standardize method is:

$$Z_{aj} = \frac{y_j^{\max} - y_{aj}}{y_j^{\max} - y_j^{\min}} \tag{25}$$

The probability of the terminal encounter with AP and its diffusion range are belong to the income-producing attribute. The standardized method of them are:

$$Z_{aj} = \frac{y_{aj} - y_j^{\min}}{y_j^{\max} - y_j^{\min}} \tag{26}$$

D. Cost Function Calculation

The calculation of cost function for selecting a candidate terminal is:

$$f(x_a) = 0.5031x_{a1} + 0.4088_{a2} + 0.0880x_{a3} \tag{27}$$

Note x_{a1}、x_{a2}、x_{a3} respectively as the value of NDT、PTD、TDR. The higher the cost function value, the better selecting the terminal as the relay-terminal.

IV. Simulation and Analysis

In a 100m long and 20m wide tunnel, a semi-active terminal is randomly selected as source terminal and the terminal communication range is 10m. AP is located in the position of 100m. For active terminals, the speed and the range of activity are respectively deployed with uniform distribution between 0.6-1m/s and 0-100m. For an-active terminals, the speed of activity are respectively deployed with uniform distribution between 0-0.5m/s, and the range of activity are deployed with uniform distribution among 0-30m, 50-60m and 70-80m. For semi-active terminals, the speed and the range of activities are respectively deployed with uniform distribution between 0.3-0.7m/s and 0-100m.

A. Network Performance Analysis

Fig. 6 exhibits the change of network-delay with the increase of terminals. When the number of terminals is small, packet is forward mainly on their own move, and the network-delay is highest. The strategy of TMM which considers the terminal diffusion range can reduce the probability that the packet be detained in a certain area for a long time, so the network-delay is lower than the predicted method based on HMPR [5]. When the terminal number increases, more terminals can encounter with AP, and network-delay of all three forwarding strategies will decline. The number of terminals continues to increase, packet can be forwarded directly to the terminal which is within the communication range. The requirement for terminal mobility decreases, finally the network-delay tends to be a constant value. Overall, we can get minimal network-delay with the Flooding method. But generally in real networks, the source terminal is less likely to be an active terminal, and the packet around it may not be transmitted to AP within its lifetime. Therefore the Flooding method is not suitable for coal mine opportunistic networks. Using TMM method can get lower latency compare with the HMPR method.

Fig. 7 exhibits the change of overhead with the increase of the terminals. Overhead means the total number of terminals carrying packet when packet is forwarded to AP. Without considering the terminal power and storage space, using Flooding method can get the lowest network-delay with the highest overhead. When the terminals store more packets with more memory and energy consumption, the terminals are easy to die as for the running out of energy or memory, so the method of Flooding not suitable for coal mine opportunistic networks. Considering terminals' limited movement range, using the method of TMM can get a higher probability to encounter better relay-terminal for packet forwarding, and get lower latency and overhead compared to the HMPR method.

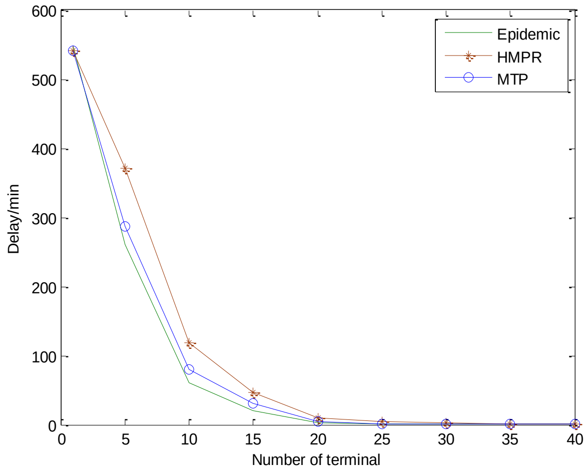

Fig. 6. Network delay over terminals increase

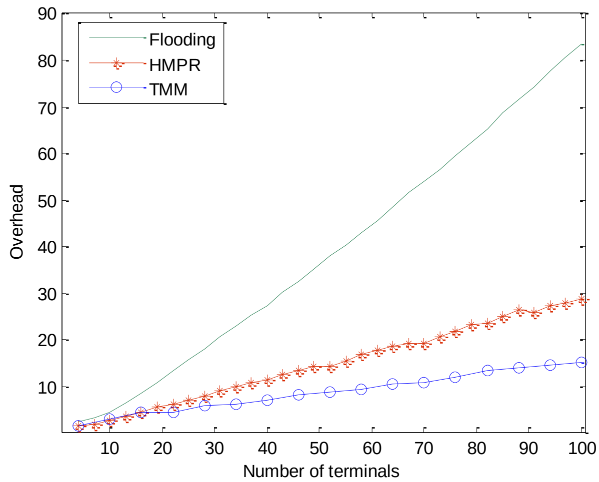

Fig. 7. Overhead over terminals increase

B. Environmental Applicability Analysis

Fig. 8 exhibits the change of network-delay with the increasing of active terminals' proportion. The total number of the terminals in coal mine is 20. When the number of active terminals is small, using the TMM method or Flooding method both can get lower network latency, but the network latency is higher when using the HMPR method. Mainly because of the limitation of terminal movement range, terminals which carry packet may have small probability of encounter with a terminal which can arrive at AP in a short time, so the packet retention time in the network is long. Gradually by increasing the proportion of active terminals, the network would have more terminals which have more chances encounter with AP. The three methods can all achieve a reduced network-delay. When terminals in network are all active, the network latency has no significantly difference. This is because the attributes of terminals have no significantly difference. As active terminals in coal mine have large movement scales and high moving speeds, packet can easily be forwarded to AP and the network delay using HMPR method has no significantly difference with the other two methods.

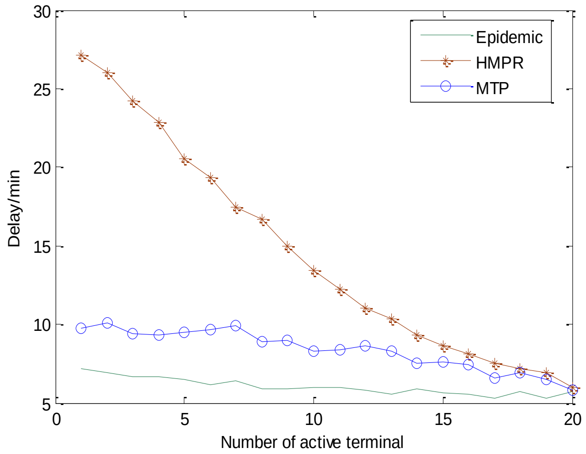

Fig. 8. Network delay over active terminals increase

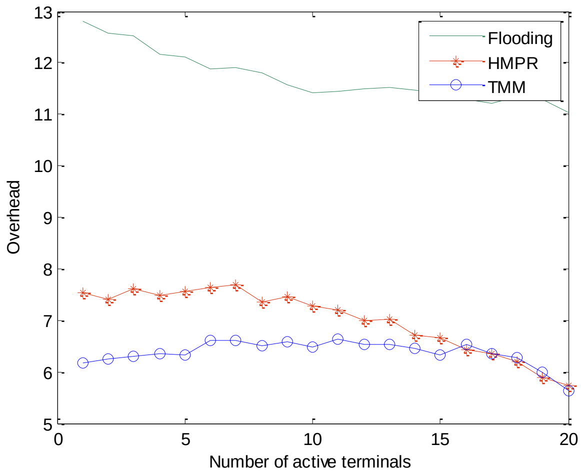

Fig. 9. Overhead over active terminals increase

Fig. 9 exhibits the change of overhead with the active terminals' proportion increases. When the number of active terminals is small, there may be no terminal around the source terminal that can encounter AP in a short time. Considering the terminal attribute of diffusion range, the TMM method increases the probability of packet forward to better relay-terminal, which result in lower latency and overhead. The Using the HMPR method, terminal which carry packet stays in a scenario for a long time, and the packet cannot be forward to AP, the overhead increases. As the proportion of active terminals increases, more terminals can carry packet to AP with large opportunity. Using the HMPR method can also get better performance than TMM method. When terminals in network are all active, the Flooding method leads to much higher overhead, the TMM method in this paper and the HMPR method have no significantly difference in overhead. This is because the attributes of terminals have no significantly difference. Active terminals can carry packet to AP with lower network latency and overhead.

When the numbers of active terminals is small, the TMM method has better performance than the HMPR method in both delay and overhead. The TMM method also has better result than the Flooding method in overhead. Conclusion

A packet forwarding protocol based on TMM is proposed for coal mine poor connectivity in opportunistic networks since its complex environment. First, a Markov model is established for predicting the probability of terminals' encounter. Then NDT、PTD、TDR are calculated based on the model, by which the best relay-terminal can be obtained to receive packet based on AHP. Simulation results show that the method can get better network performance in the condition of limited terminal movement range and big difference in terminals' attribute. But it still have large waste of overhead when there are large number of terminals in network, how to discard the outdated data packet to improve the network performance is important in next stage research.

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