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A location aided controlled spraying routing algorithm for Delay Tolerant Networks

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Abstract—Delay Tolerant Networks (DTNs) often suffer from intermittent disruption and variable long delay due to factors such as mobility and energy. In this paper, a Location Aided Controlled Spraying (LACS) routing algorithm is proposed to deal with the challenging issues in DTN routing. Only the routing information carried by the contacted nodes is needed in this algorithm, and there is no need for global networks knowledge and hardware support. The routing process is divided into two stages, i.e., controlled spraying routing stage and single-copy routing stage. The maximum transfer throughput of the contact is checked before each message is forwarded. During the controlled spraying stage, the current node adjusts spraying strategy according to the encounter angle of the contact nodes. During the single-copy stage, a location prediction model based on the semi-Markov process (SMP) is introduced, and the node's behaviors can be captured both in the temporal and spatial domains with this model. The current node predicts the destination node's location, and then decides whether to forward the message to target node based on the time used for meeting the destination node. Simulation results show that the proposed algorithm can achieve better performance than the traditional routing schemes of DTNs in terms of delivery ratio, network overhead and transmission delay under both random node movement model and realistic trace scenario.

Keywords–delay tolerant networks; semi-Markov process; location prediction; nodes contact; spraying routing

1. INTRODUCTION

Delay Tolerant Networks (DTNs) [1] are designed to cope with the challenging conditions in the restricted networks with sparse density, intermittent disruption and limited energy. DTNs have features such as multiple hops, self-organization, and no central administration. In DTNs, an end-to-end path between a source node and a destination node does not exist most of the time, and the messages are opportunistically routed. Therefore, routing is an extremely challenging problem due to the characteristics of DTNs and the traditional network routing techniques cannot work effectively in DTNs [2].

There have been different kinds of routing schemes proposed for DTNs in recent years, and typical schemes include epidemic routing and probabilistic routing. The epidemic routing can achieve high delivery ratio and small delay at the cost of network bandwidth and buffer space by flooding messages to all the nodes encountered. To reduce the consumption of network resource, it uses different ways to limit the number of message copies forwarded, but it is hard to distinguish between nodes with regard to their probabilities of delivering the messages. The probabilistic routing tries to reduce message overhead and buffer contention by forwarding messages to nodes only with high delivery probabilities. Its difficulty lies in the determination of reasonable delivery probability and the applicability in different scenarios.

In this paper, a novel routing algorithm called Location-Aided Controlled Spraying (LACS) is proposed. Despite the fact that a number of existing protocols have used location-aided methods, there are few routing schemes that consider rational assumptions for DTNs and have low complexity [3] [4]. The proposed scheme combines the advantages of both spraying routing and probabilistic routing. The scheme consists of two stages according to the amount of the message copies: the controlled spraying stage and the single-copy location aided routing stage. If message copies are more than one, the message is forwarded by the spraying method, and the spraying process is controlled by node encounter angle instead of binary mode. By this, the copies can be spread to the whole region more quickly and avoid the slow start problem [5]. When only one copy is left, the LACS will trigger the single-copy routing stage aided by the location information. The location prediction model is based on the SMP, and all the needed information can be obtained from the two contact nodes. The last copy of the message will be forwarded to the node which can reach the destination within the shortest time.

The major contributions of this paper are as follows. (1) A method to estimate the throughput of node contact is proposed. It can help avoid transmitting such messages that could not be finished within the contact time. (2) An angle related adaptable spraying strategy is developed to increase the message propagation efficiency. (3) A location prediction model based on the SMP is devised to find the superior relay node in the one-copy routing stage. (4) Simulations are implemented in both synthetic movement models and realistic traces to demonstrate the superior performance of the proposed LACS scheme over several representative routing algorithms.

The remaining sections of this paper are organized as follows. In Section 2, the state-of-the-art routing algorithms in DTNs are briefly reviewed. In Section 3, the location-aided spraying routing algorithm is proposed and analyzed. The simulation results under different nodes mobility models are presented in Section 4. Finally, Section 5 concludes the paper and points out the future work.

2. RELATED WORK

There are many kinds of DTN routing schemes and different ways to categorize them [6]. In this paper, they are categorized into two types: coding-based routing and copy-based routing.

2.1. coding-based routing protocols

Motivated by transmitting large size data, for example, big files in DTNs, coding-based routing protocols are proposed against the limited transmission opportunities by relaying buffers in realistic network settings. In the coding-based routing protocols, the source node converts one generated message into multiple coding blocks and transmits them in the DTNs, and the destination node restores the original message after receiving the certain amount of coding blocks. There are mainly two kinds of coding-based routing protocols: erasure coding and network coding.

In [7], an erasure coding based forwarding algorithm is proposed, which spreads the forwarding responsibility over many nodes while maintaining a fixed network overhead. However, this scheme increases the transmission delay in most cases. In [8], the adaptive erasure coding routing schemes are proposed for interplanetary networks, which are effective even in case of imperfect transmission channel knowledge. The incremental redundancy adaptation (IRA) and partially observable Markov decision process (POMDP) approaches are analyzed in the coding round, and the appropriate decision about coding strategy selection can be taken based on incomplete knowledge. In [9], an erasure coding framework integrated within the DTN architecture is introduced, which extends the bundle protocol specification. In this scheme, the transmission robustness against link interruptions and disruption is improved by the joint use of a packet level coding approach with the custody transfer option. In [10], a routing algorithm is proposed by combining the erasure coding and replication to handle the path failures in DTNs. Both Bernoulli path delivery model and Gaussian path delivery model are discussed to solve the underlying optimization problem. The erasure coding based scheme is robust to failures of a few relay nodes, but it also results in underperformance because of the limited storage capacity and long transmission delay in DTNs.

The network coding is defined as allowing intermediate nodes to not only forward but also combine their incoming independent information flows. The network coding based probabilistic routing is proposed in [11], which can reduce the overhead of probabilistic routing algorithms. The nodes do not simply forward packets which they overheard, but may send out information that is coded over the contents of several packets they received. The network coding based epidemic routing (NCER) scheme is proposed in [12], which transmits a batch of data packets with network coding. In [13], an efficient network coding based protocol (E-NCP) is proposed to optimize packet transmission efficiency, achieving similar transmission delay but with much fewer transmissions. In this scheme, the source node transmits slightly more coded packets such that these coded packets are sufficient to decode the original packets with high probability. The coded packets are referred to as pseudo source packets and disseminated by binary spraying. In [14], an efficient context-aware network coding (CANCO) scheme for DTNs is proposed, in which the nodes move according to non-homogeneous mobility models. The friendliness metric is used to measures how popular a node is while the delivery predictability estimates the probability of reaching another node. The most compelling benefits of network coding may be its robustness and adaptability, which can significantly increase throughput for different traffic patterns. However, network coding also increases communication complexity and is not suitable for the resource constrained DTNs nodes. Therefore, in our scheme, the coding-based method is not used because we are trying to find a simple but effective method which has low demand for node performance and network resource.

2.2. copy-based routing protocols

In the copy-based routing, the source node generates one message and then injects one or more copies into the networks. The relay nodes will forward this message to the destination node by different routing algorithms. The copy-based routing protocols can be classified into single-copy routing and multi-copy routing, and the latter type is in the majority.

In the single-copy routing schemes, a prediction assisted algorithm is proposed for underwater DTNs [15], which uses the aggressive chronological projected graph (ACPG) to capture the network mobility properties and the common characteristics of near optimal routes. Then based on the guidance from ACPG, the online heuristic protocol is devised by choosing appropriate historical information and forwarding criteria. In [16], several basic single-copy routing protocols are discussed such as direct transmission, randomized routing, utility-based routing with 1-hop diffusion, utility-based routing with transitivity, seek and focus routing, oracle-based routing and so on. In [17], a predict and relay routing algorithm is presented in which the nodes determine the probability distribution of future contact times and choose a proper next hop to improve the end-to-end delivery probability. It assumes that the nodes move around a set of well-visited landmark points and their mobility behaviors are described by time-homogeneous semi-Markov process model. The single-copy routing scheme has excellent performance at the expenditure of network resource, but performs poor at other aspects such as message delivery ratio, delay and so on. This kind of routing scheme is appropriate for the scenario where nodes and networks are extremely resource constrained, so it is not applied in our proposed scheme.

The multi-copy routing is the most discussed case in recent years. The epidemic routing is a typical one, in which nodes exchange all different messages they carry and try their best to transmit messages to destination nodes. However, this will lead to too much network resource expenditure. There are some kinds of methods to avoid message flooding: probabilistic routing, social based routing and controlled epidemic routing.

The probabilistic routing determines whether a message between two contacted nodes is transmitted by a certain algorithm. The Prophet routing algorithm is proposed in [18], which uses history information of previous encounters to estimate delivery probability. Pair of nodes that encountered often in the past have high delivery predictability, and each node selects the messages that have high possibility to reach the intended destinations and transfers them to its contact node. The MaxProp routing scheme is proposed in [19], which can calculate the total cost of forwarding a message to the destination, and gives the high priority to the copy that has high delivery probability. The probabilistic routing can reduce network resource expenditure, but its performance relies on accuracy and timeliness of history information. Our proposed scheme considers both time and space factors in order to reduce the influence of the outdated history information on the routing policy.

The social network analysis is also used for DTNs routing schemes in recent years. The SimBet routing algorithm is proposed in [20], which uses the small world dynamics to find some bridge nodes based on the centrality characteristics, and the 'betweenness' and 'similarity' are estimated to calculate the node's utility. On this basis, the BUBBLE scheme [21] selects high centrality nodes and community members of destination as relays. The k-clique community detection method and weighted network analysis are used to explore the structure of the human mobility traces. A friendship based routing in proposed in [22], and the temporally differentiated friendships are introduced to make the forwarding decisions of messages. The sociable routing scheme is proposed in [23], which chooses the set of best forwarders among those having high sociability indicators, which are related to the social characteristics of networks nodes by capturing the frequency and type of their encounters. For the social based routing schemes, how to accurately describe the social features of nodes in the dynamic DTNs and balance the positive and negative influence of sociality are the key issues.

The controlled epidemic routing limits the number of copies injected into the networks. In [24], the spray and wait (SAW) routing algorithm is presented, in which a certain number of copies are sprayed into the networks. This algorithm waits until one of these nodes with this message meets the destination. The SAW routing can be viewed as a tradeoff between single-copy schemes and multi-copy schemes. The Spray and Focus (SAF) [25] is a modification over SAW, which is designed for a specific scenario where the node mobility is limited to a small area for most of the time. The difference between SAW and SAF lies in the second phase, while the single-copy utility based routing is performed in SAF. Based on the two algorithms mentioned above, some other spray based schemes are proposed such as time dependent message spraying [26], multi-period spraying [27], and fuzzy-spraying [28]. These schemes focused on the improvement of the spray efficiency. The spraying method used in our scheme is related to the encounter angle, which is simple but can effectively increase the message's transmission chance. The location information is important and useful for the routing in mobile wireless networks, so it is also used to limit the amount of message copies ejected into the network.

The location-aided routing algorithms have been studied extensively following the early work in [29]. In [30], the greedy forwarding is proposed for mobile ad hoc networks, in which each node forwards the packet to the neighbor closest to the destination among all its neighbors. In [31], a stochastic location-aided routing algorithm is proposed to optimize the tradeoff between the message passing overhead and the delay. In [32], an epidemic routing protocol with H and T matrices (EPI-HT) is proposed, which tries to forward messages accurately to the next-hop according to the historical information. In [33], a spray and forward routing algorithm is proposed, which uses the Markov forecasting mechanism to predict the location of the destination node, and then forwards the message by the greedy routing. Most of these schemes need the passively updated node location database which is built by message exchange. However, since the location information exchanged in DTNs cannot be updated in time, it often leads to great difference between the real location and the stored location. In our proposed location prediction model, time is also considered as a variable to predict the location, and the current node location is related to not only the location at the last recorded moment but also the length of the time interval. When two nodes are in contact, only the locations of the encountered nodes are exchanged, which can reduce error propagation and get more accurate prediction results.

3. THE PROPOSED ALGORITHM

In this section, first both the maximum throughput estimation of node contact and the controlled spraying stage of the proposed LACS algorithm are introduced, then both the SMP based location prediction model and the single-copy routing stage of LACS are described, and the algorithm procedure is provided at the end.

3.1. The controlled spraying stage based on the contact

The development of positioning technology makes it possible to get mobile node positions easily, cheaply and precisely. The widely used positioning techniques include satellite positioning, wireless positioning and base station positioning. Especially for the satellite positioning, there are global position system (GPS), Galileo satellite navigation system, BeiDou satellite navigation system (BDS) and so on. Therefore, the assumption that the node is aware of its location is rational.

Due to the features of DTN, the location information exchange just happens when two nodes encounter. The contact time means how long the nodes are in the range of each other from being connected to being disconnected. It can reflect the maximum throughput in the contact duration and the throughput decreases with the time. The transmission fails if the message size is greater than the maximum throughput left. This leads to the energy and bandwidth waste. In the paper, a maximum throughput estimation method is proposed, which is carried out before each message is forwarded, and this can greatly decrease the amount of unfinished message transmission. The maximum throughput in a contact is related to the node's movement speed and direction as well as its transmission range and speed. Because most of the contacts last no more than few tens of seconds, the transmission scene can be considered as a two-dimensional model, and the movement speed and direction are assumed constant in one contact time.

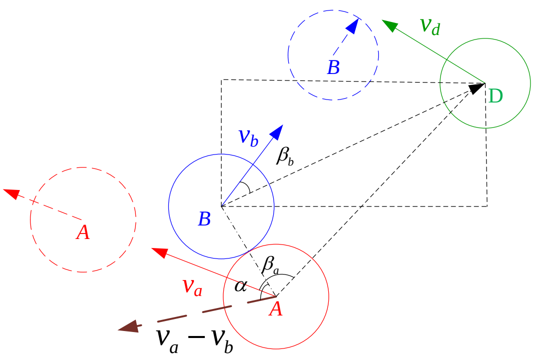

Fig.1 The encounter model of nodes

Given two contacted nodes A and B as shown in Fig.1, with speed v_a and v_b, transmission range r_a and r_b, transmission rate T_a and T_b respectively, the contact angle α between the two nodes can be calculated as follows:

$$\alpha = \arccos\frac{v_a \cdot v_b}{|v_a||v_b|} \tag{1}$$

Here, the angle $\alpha \in [0, \pi]$. Then, the contact duration time t_d can be calculated as follows:

$$t_d = \frac{2(r_a + r_b)\cos\alpha}{|v_a - v_b|} = \frac{2(r_a + r_b)(v_a \cdot v_b)}{|v_a - v_b||v_a||v_b|} \tag{2}$$

From Eq.(1) and Eq.(2), the maximum throughput C_{max} of this contact can be calculated as follows:

$$C_{\max} = t_d \times T_s \tag{3}$$

Certainly, C_{max} decreases gradually after the contact begins. Then, assume that the contact begins at the moment t_b, and the remaining maximum throughput C_{t_m} at the moment t_m can be calculated as follows:

$$C_{t_m} = (t_d - (t_m - t_b)) \times T_s \tag{4}$$

Once the maximum throughput has been obtained, the node firstly checks whether it is greater than the size of the message. If this condition is not met, the node terminates the transmission and goes to next message.

If the message can be transmitted successfully within the contact time, the next issue is how to spray the copies into the network. The traditional binary spraying is simple but not efficient. The message should be spread into the network as soon as possible to increase the delivery ratio and decrease the transmission delay. In order to increase the message's transmission chance in the resource constrained condition, a controlled spraying method is proposed which can adjust the spraying strategy based on the encounter angle, which is superior to the binary spraying both in the efficient and speed. In our spraying method, if the encounter angle is between $[0, \pi/2]$, this means that the two encounter nodes move at a similar direction, and they may appear in close area after a period of time. In this situation, the nodes exchange fewer copies of the message between each other. On the other hand, the angle between $(\pi/2, \pi]$ means that the two nodes move at quite different directions, and they may appear in relatively further distance later. Therefore, more copies should be exchanged to spread the message more quickly and widely. This method can reduce congestion and avoid spraying too many redundant copies.

The proposed controlled spraying stage can be described as follows. When two nodes *A* and *B* encounter, they exchange the motion information and the abstract information of all messages which is called summary vector (SV). Taking node *A* as an example, it computes the encounter angle and estimates the maximum throughput of this contact, and then adopts the controlled spraying based on the calculation. The amount of copies to be forwarded can be obtained by the following algorithm, i.e., Algorithm 1.

Algorithm 1 Controlled_spraying

```
Input: Message transmission queue of node A: Q_m; Maximum throughput: C_t;
       Number of message copies: N_r; Size of message: S_m
Output: The amount of copies to be forwarded: N_f
for each contact of node A
    while Q_m != null
        Update C_t;
        for each message m in Q_m
            if C_t > S_m && N_r > 1 then
                if 0 ≤ α ≤ π/2 then
                    N_f = 1;
                elseif π/2 < α ≤ π
                    N_f = [N_r / 2];
                end if
            else
                Remove m from Q_m;
            end if
        end for
    end while
end for
return N_f;
```

3.2. The single-copy routing stage based on location prediction

The case that a message is forwarded with only one left copy is discussed in this section. Just one copy of the message left means that some copies have been ejected into the network, thus it is necessary to find a relay node superior over the current node. In this section, a location prediction model based on the Semi-Markov Process (SMP) is introduced to support the forwarding of the last copy.

3.2.1 The SMP based location prediction model

Some location prediction models have been proposed for the nodes in wireless networks, such as the aggressive chronological projected graph [15], the LZ-based predictors [34] and the Markov-based models [35]. These models try to predict the node's location from recent history information. They are effective only when location data are precise and timely, and some of them need to observe the node's movement over a long period of time. Unfortunately, the long delay and frequent disruption in DTNs make it hard to exchange history location information timely and effectively. The SMP model proposed in the paper tries to overcome this difficulty by the joint use of time and location factors, in which the node's current location is predicted by the latest location of the node and the corresponding time, and all the required information can be obtained from the nodes in contact.

In order to establish the location prediction model, the whole communication region is divided into some grid zones as shown in Fig.2, and the grid size depends on the node transmission range. At any given moment one node is in a certain grid zone, and the central point coordinates of the zone can be used as the approximate location of the node. It is assumed that there are n different grid zones in total, and $L_i(x_i, y_i), i \in 1 \ldots n$, is the central point coordinates of the i^{th} grid zone, which is also used as the node position in this grid zone. Because the current location of the node is related to both its previous position and the duration time, the node's movement can be described as a SMP. As shown in Fig.3, the location represents node's state, and the state transition probability is related to the last state and the duration time at that state [36].

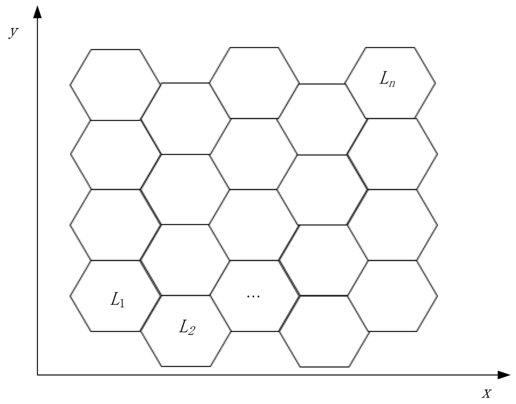

Fig.2. Divided grids in communication region

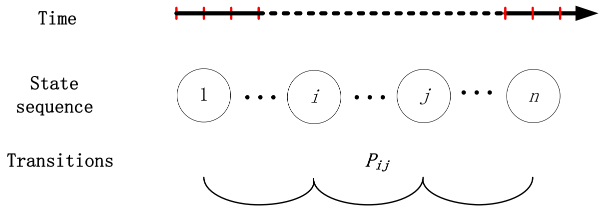

Fig.3. State sequence and transition probability

It is supposed that there is a semi-Markov process $Z = \{Z_t, t \geq 0\}$ and the K_{ij} is defined as the kernel function of this process as follows:

$$K_{ij} = \Pr(L_{n+1} = j, T_{n+1} - T_n \leq t \mid L_n = i) = P_{ij} H_{ij}(t) \tag{5}$$

$P_{ij} = \Pr(L_{n+1} = j \mid L_n = i)$ is the transition probability from state i to state j. The matrix $P = \{P_{ij}\}$ is used to denote the transition probability matrix of the random process and is formulated as follows:

$$P = \begin{bmatrix} P_{11} & \cdots & P_{1j} & \cdots & P_{1n} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ P_{i1} & \cdots & P_{ij} & \cdots & P_{in} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ P_{n1} & \cdots & P_{nj} & \cdots & P_{nn} \end{bmatrix} \tag{6}$$

H_{ij} is used to denote the residence time distribution from state i to state j and it is defined as follows:

$$H_{ij} = \Pr(T_{n+1} - T_n \leq t \mid L_n = i, L_{n+1} = j) \tag{7}$$

$D_i(t)$ is used to denote the duration time distribution at state i under the condition where next state is not considered. It is defined as follows:

$$D_i(t) = \Pr(T_{n+1} - T_n \leq t \mid L_n = i) = \sum_j K_{ij}(t) \tag{8}$$

In fact, it is difficult to obtain $D_i(t)$ of the destination node directly. However, the residence time distribution of the current node can be used to estimate the residence time distribution of the destination node. It is described as normal distribution and the parameters are achieved from the records stored in the current node. Suppose that one node has l location records and the duration time is t_i, $i \in 1 \ldots l$, its residence time distribution can be expressed as follows:

$$D_i(t) \sim \frac{1}{\sqrt{2\pi}\delta}\exp\left(-\frac{(x-\mu)^2}{2\delta^2}\right) \tag{9}$$

Here, $\mu = \frac{1}{l}\sum_{i=1}^{l} t_i$, $\delta = \sqrt{\frac{1}{l}\sum_{i=1}^{l}(t_i-\mu)^2}$.

Then the transient distribution of the semi-Markov process is denoted as $f_{ij}(t)$ and it is defined as follows:

$$\begin{aligned} f_{ij}(t) &= \Pr(Z_t = j \mid Z_0 = i) \\ &= (1 - D_i(t))\delta_{ij} + \sum_{l=1}^{s}\int_0^t f_{lj}(t-\tau)\,dK_{il}(\tau) \\ &= (1 - D_i(t))\delta_{ij} + \sum_{l=1}^{s}\int_0^t K'_{il}(\tau) f_{lj}(t-\tau)\,d\tau \end{aligned} \tag{10}$$

Here, δ_{ij} denotes the Kronecker symbol, which is a function of two variables. Its value is 1 if the two variables are equal, and 0 otherwise. It is defined as follows:

$$\delta_{ij} = \begin{cases} 0 & i \neq j \\ 1 & i = j \end{cases}$$

The first part of Eq.(10) is the probability that the system does not have transition up to time t given that it was in state i at time 0. In the second part of Eq.(10), $K'_{il}(\tau)$ is the derivative at time τ of $K_{il}(\tau)$ and is the probability that the system remains in state i up to time τ and transits into state l just at time τ. After the transition from state i to l, the system transits into state j following one of the possible trajectories from state l to state j.

By means of the quadrature method, it is easy to find a numerical solution of Eq. (10) which converges to the discrete time semi-Markov process [37]. By performing the discretization of Eq. (10) with step h, we can get the followings:

$$f_{ij}(kh) = (1 - D^h_i(kh))\delta_{ij} + \sum_{l=1}^{s}\sum_{\tau=1}^{k} v_{il}(\tau h) f^h_{lj}((k-\tau)h) \tag{11}$$

We further get the approximate $K'_{il}(kh)$ in the expression of $v_{il}(kh)$ as follows:

$$v_{il}(kh) = hK'_{il}(kh) = \begin{cases} \tilde{K}_{il}(h) & k = 1 \\ \tilde{K}_{il}(kh) - \tilde{K}_{il}((k-1)h) & k > 1, \end{cases}$$

Where $\tilde{K}_{il}(kh)$ is the empirical distribution of $K_{il}(t)$, obtained from the historical data.

In fact, $f_{ij}(kh)$ is the transition probability of a node from state i to state j, and the node has been in state i lasting kh time.

The $f_{ij}(k)$ can be derived from the iterative method shown in Eq. (12).

$$f^h_{(kh)} - \sum_{\tau=1}^{k} V^h_{(\tau h)} f^h_{((k-\tau)h)} = D^h_{(kh)} \tag{12}$$

Then, we can get the followings:

$$U^h \cdot \Phi^h = D^h \quad (13)$$

Here,

$$U^h = \begin{bmatrix} 1 & 0 & 0 & 0 & \cdots \\ V_h^h & 1 & 0 & 0 & \cdots \\ V_{2h}^h & -V_h^h & 1 & 0 & \cdots \\ V_{3h}^h & -V_{2h}^h & -V_h^h & 1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}, \Phi^h = \begin{bmatrix} \phi_0^h \\ \phi_h^h \\ \phi_{2h}^h \\ \phi_{3h}^h \\ \vdots \end{bmatrix}, D^h = \begin{bmatrix} D_0^h \\ D_h^h \\ D_{2h}^h \\ D_{3h}^h \\ \vdots \end{bmatrix}.$$

Obviously, $\phi_0^h = 1$, and ϕ_h^h can be obtained by $\phi_h^h = V_h^h \cdot \phi_h^h + D_h^h$. Once $\phi_0^h, \phi_h^h, \ldots, \phi_k^h$ are known, we can get the followings:

$$\phi_{((k+1)h)}^h = \sum_{t=1}^{k+1} V_{(th)}^h \phi_{((k+1-t)h)}^h + D_{((k+1)h)}^h \quad (14)$$

So the transient distribution probability matrix $\Phi = \{\phi_{ij}\}$ is calculated from Eq. (13) and denoted as follows:

$$\Phi = \begin{bmatrix} \phi_{11} & \cdots & \phi_{1j} & \cdots & \phi_{1n} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ \phi_{i1} & \cdots & \phi_{ij} & \cdots & \phi_{in} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ \phi_{n1} & \cdots & \phi_{nj} & \cdots & \phi_{nn} \end{bmatrix} \quad (15)$$

If the matrix Φ is known, the location of a node can be predicted by finding the largest entry in the i^{th} row. The corresponding column for this entry is the most possible location that the node will be after time Δt.

3.2.2 The single-copy routing based on location prediction

If the message to be forwarded has only one copy left, the proposed scheme enters the single-copy routing stage. In this case the message should be forwarded to a relay node superior over the current node. For the contact nodes, the superior node is the one which can meet the destination node earlier. In this section the location information is used to estimate the time one node need before having contact with the destination node, and whether to forward the message or not is judged with the aid of the estimation.

Suppose that the locations of contact nodes *A* and *B* are $L_a(x_a, y_a)$ and $L_b(x_b, y_b)$, and the predicted location of destination node *D* is $L_d(x_d, y_d)$. The vectors between the contact nodes and destination node are calculated by $\overrightarrow{AD} = (x_d - x_a, y_d - y_a)$, $\overrightarrow{BD} = (x_d - x_b, y_d - y_b)$. The angles between the location vectors and velocity vectors are calculated as follows:

$$\beta_{ad} = \arccos \frac{\overrightarrow{AD} \cdot v_a}{|\overrightarrow{AD}||v_a|}, \quad \beta_{bd} = \arccos \frac{\overrightarrow{BD} \cdot v_b}{|\overrightarrow{BD}||v_b|}. \tag{16}$$

Then the needed time t_{ad} and t_{bd} for the contact nodes to encounter destination node can be estimated as follows:

$$t_{ad} = \frac{\sqrt{(x_a - x_d)^2 + (y_a - y_d)^2}}{v_a \cos \beta_{ad}}, \quad t_{bd} = \frac{\sqrt{(x_b - x_d)^2 + (y_b - y_d)^2}}{v_b \cos \beta_{bd}} \tag{17}$$

Whether or not to forward the message from node *A* to node *B* is based on the comparison of t_{ad} and t_{bd}. If $t_{ad} > t_{bd}$, node *A* will forward this message to *B*, otherwise it will do nothing and process the next message. Algorithm 2 gives the detailed procedure of single-copy routing stage.

Algorithm 2 Single_copy_routing

Input: Message transmission queue of node *A*: Q_m; Maximum throughput C_t; Number of message copies: N_r; Size of message: S_m; Location vector: $(L_1, L_2, \ldots, L_n)$; Time vector $(t_1, t_2, \ldots, t_n)$;

Output: The amount of copies to be forwarded: N_f

```
for each contact of node A
    while Q_m != null
        Update C_t;
        for each message m in Q_m
            if C_t > S_m then
                while N_r == 1
                    Replace L_d (x_d, y_d) by SMP prediction model;
                    Calculate t_ad and t_bd;
                    if t_ad > t_bd then
                        N_f =1;
                    else t_ad < t_bd
                        N_f =0;
                    end if
                end while
            else
                Remove m from Q_m;
        end for
    end while
end for
return N_f;
```

3.3. The location-aided controlled spraying routing

The features of the proposed LACS routing algorithm have been described in the above sections, and the following is the detailed description. It assumes that the nodes adopt the First Input First Output (FIFO) buffer management policy.

If two nodes are in contact at one moment in the LACS routing scheme, they firstly exchange routing related information, such as location matrix, speed, index of *SV*. Suppose node *A* is the current node and node *B* is the target node. In order to form the message transmission queue, node *A* drops the message which is outdated or has been transmitted. The size of each message in the queue is compared to the remaining throughput of the contact before forwarding. When the throughput meets the transmission requirements, the LACS enters the controlled spraying stage or the single-copy routing stage according to the amount of the message copies. The angle related adaptable spraying is introduced in the controlled spraying stage, and the SMP based location prediction is used in the single copy routing stage. For the target node *B*, it deals with the received message based on the message type. The transmission queue of node *B* will be updated after receiving acknowledgment message, and the data message will be stored and an acknowledgment message will be sent to node *A*. The detailed procedure of the LACS scheme is described in Algorithm3.

Algorithm 3 LACS routing algorithm

Input: Encountered nodes(*A*, *B*) ;
Output: The amount of copies to be forwarded: N_f
for each contact between *A* and *B*
  Exchange routing information;
  Establish message transmit queue of node *A*: Q_m
  Calculate encounter angle: $\alpha = \arccos \frac{v_a \cdot v_b}{|v_a||v_b|}$;
  Get the maximum throughput of node *A* in the contact:
    $C_{\max} = t_d \times T_a$;
  while Q_m != null
    for each message *m* in Q_m
      Update the remaining maximum throughput:
        $C_{t_m} = (t_d - (t_m - t_b)) \times T_a$;
      if $C_{t_m} > S_m$ **then**
        if $N_r > 1$ **then**
          Goto Controlled_spraying_routing algorithm;
        elseif $N_r == 1$
          Goto Single_copy_ routing algorithm;
        end if
      else
        Remove *m* from Q_m;
      end if
    end for
  end while
end for
return N_f

---

4. SIMULATION AND ANALYSIS

The simulation experiments are implemented over the ONE simulator [38]. It allows users to create scenarios based upon different synthetic movement models and real-world traces and offers a framework for implementing routing and application protocols. The Epidemic, SAW and MaxProp are used as performance comparison benchmarks. The Epidemic is a fundamental routing protocol for DTNs, and the SAW is a typical spraying scheme by limiting the number of message copies forwarded, and the MaxProp is a probability routing scheme based on prioritizing messages to be transmitted and dropped. The metrics used in the performance evaluation include average message delivery ratio, end-to-end message delay and network overhead ratio. The network overhead ratio is defined as the ratio of the number of forwarded messages to the messages successfully delivered.

4.1. Simulation results in RWP movement model

In this section, the LACS, Epidemic, SAW and MaxProp are simulated with RWP movement model. The total number of nodes in the network is 200. The whole simulation time is 45000 seconds, and the initialization time is 1800 seconds. The detailed simulation parameter settings are summarized in Table I.

TABLE 1 Simulation parameters

Parameter	Value
Simulation area	4, 500 $\times$ 3, 400 m
Node bandwidth	2 Mbps
Node velocity	0.5 ~ 1.5 m/s
Node transmit range	20 m
Message size	0.5 ~ 1 MB
Message TTL	3, 600 s
Initial energy of node	10000 mA•h
Energy expenditure per scan	10 mA•h
Transmit energy expenditure per sec	20 mA•h

The comparison results are shown in Figs. 4-6. As shown in Fig. 4, the LACS scheme has much better performance in delivery ratio than the SAW and Epidemic, and slightly outperforms the MaxProp. When the buffer space is smaller than 20MB, the delivery ratio of SAW increases stably, but the delivery ratios of other three schemes grow rapidly, and the LACS has a similar growth trend as the MaxProp. With the increase of the buffer space, the delivery ratio of LACS will increase slightly. The reason is that the Maxprop is a kind of probabilistic routing, and it needs more message copies to improve delivery ratio. The SAW scheme restricts the number of message copies to a fixed value, thus the buffer space has less influence on it. The LACS has message forwarding process in the second stage, thus the delivery ratio increases with the buffer storage. The LACS adopts throughput capacity estimation and location assisted methods to enhance the purpose of the message transmission, and it always achieves better performance except some extreme cases such as a very small memory.

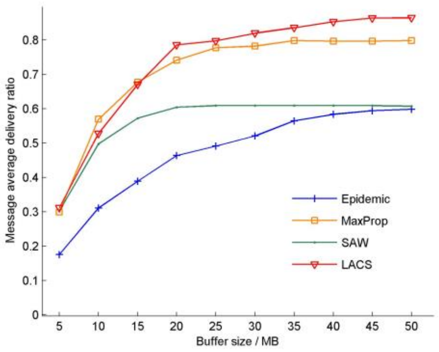

Fig.4. Delivery ratio vs buffer size under RWP movement model

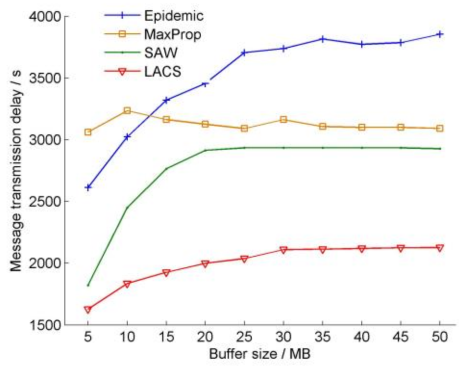

Fig. 5. Delay vs buffer size under RWP movement model

As shown in Fig. 5, the LACS scheme has the lowest end-to-end message delay among the four routing algorithms. The Epidemic has the longest transmission delay and the MaxProp also has poor performance in this respect. In SAW and LACS, the delay will increase when the buffer space is less than 20 MB and then remains nearly unchanged with the increase of the buffer space. The reason is that more message copies are forwarded with the increase of buffer size in Epidemic and MaxProp, and the message copies number are limited in SAW and LACS. The location aided method reduces the delay further.

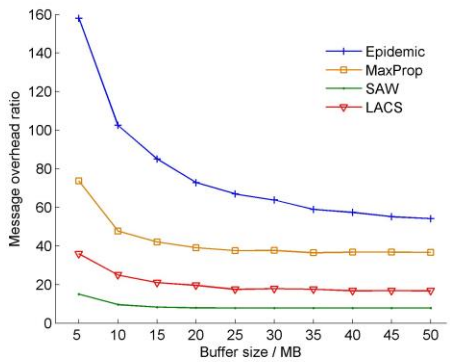

Fig.6. Overhead ratio vs buffer size under RWP movement model

As illustrated in Fig. 6, the SAW has the best performance in the message overhead ratio because it just forwards message to the destination node in the wait phase. The LACS still forwards copy to some appropriate nodes, however, the single-copy routing method in its second stage brings the improved performance compared to Epidemic and MaxProp. The Epidemic and MaxProp do not limit the number of copies, thus they have poor performance in the message overhead ratio aspect.

4.2. Simulation results in realistic trace

In this case, the Dartmouth trace is applied in the simulation [36], which was collected by several thousand wireless laptops carried by students and faculties at the Dartmouth College campus. All users are sorted in a descending order of trace length and 200 users are selected as the nodes for simulation. The parameters of the nodes are the same as in section 4.1, and the comparison results are shown in Figs. 7-9.

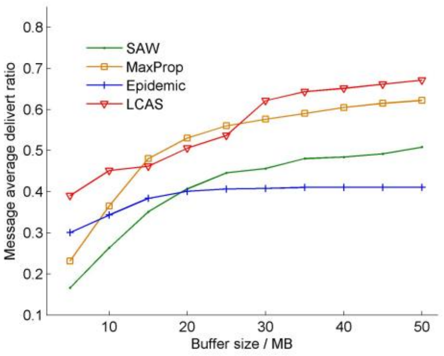

Fig.7. Delivery ratio vs buffer size under Dartmouth trace

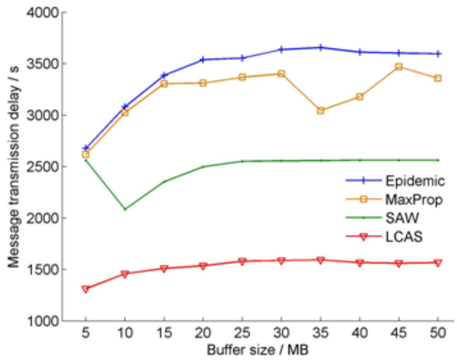

Fig.8. Delay vs buffer size under Dartmouth trace

As shown in Fig. 7 and Fig. 9, the delivery ratio of the four routing schemes under Dartmouth trace is slightly less than the one under RWP movement model. However, the network overhead ratio of the four routing schemes under Dartmouth trace is approximately doubled compared to RWP movement model. The reason is that the nodes in RWP movement model have more contacts than in the realistic trace, and the contacts can increase the delivery ratio while reducing the networks overhead ratio. As shown in Fig. 8, the message transmission delay of the four routing schemes under Dartmouth trace has not changed substantially in contrast to RWP movement model. This is because that the delay is mainly related to the routing algorithm, and that the contact chance does not have much effect on the transmission delay.

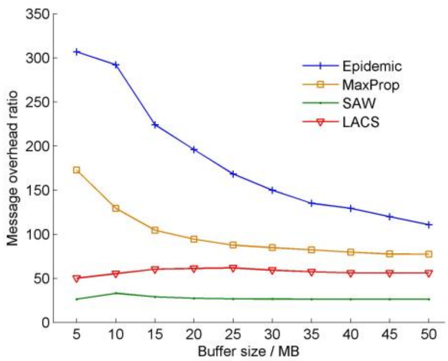

Fig.9. Overhead ratio vs buffer size under Dartmouth trace

5. CONCLUSION

To improve message forwarding efficiency in DTN routing, in this paper a novel routing scheme assisted by location information is proposed with spraying stage and single-copy routing stage. It adopts throughput estimation for every contact to avoid unnecessary message forwarding. In the spraying stage, the number of copies to be forwarded is based on the encounter angle when nodes meet. In the single-copy routing stage, whether or not to forward the last copy to another node is related to the arrival time to destination node and the time is estimated with the location prediction model based on the SMP. We analyze the prediction model and develop the method to obtain the parameters of SMP model by contact information. Simulation results show that the proposed scheme has better performance than some typical routing algorithms for DTNs under both random movement model and realistic trace. In the future, we plan to improve the location estimation precision by finding the optimal values of the parameters in the SMP model, and refine the proposed scheme to deal with other different challenging network environments, such as throwbox-equipped DTNs [39], vehicular DTNs [40] and so on.

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