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Heterogeneous Community-based Routing in Opportunistic Mobile Social Networks

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***Abstract*—With the recent technical advances and popularization of smartphones, which are able to store, display, and transmit various types of media content, message forwarding in opportunistic mobile social networks has become a hot topic. In this paper, we propose a social-aware single-copy routing approach, which leverages the internal social feature information to resolve the social distance between the source and destination step-by-step. We introduce an optimal social feature forwarding set selection scheme for routing guidance, which is proven to achieve small message forwarding delay. We convert the routing process into an iterative 2-hop routing scheme, with a novel transition probability to measure the delivery delay of each hop. The transition probability is according to the community structure in each social feature space. Extensive simulations on both real and synthetic traces are conducted in comparison with several existing state-of-art approaches.**

***Index Terms*—Opportunistic mobile social networks, optimal forwarding set, single-copy, social features.**

I. Introduction

Opportunistic mobile social networks (OMSNs) are designed to operate without the supports of preset infrastructures and guaranteed network connectivity. In these networks, mobile nodes exploit node mobility and opportunistic contacts for communication while coping with such intermittent connectivity, which enables eventual message delivery even if end-to-end paths never exist.

Several social-aware routing schemes [1, 2, 5, 9, 14, 16, 17] have been proposed in OMSNs. Most of these approaches leverage the contact history or mobility pattern to predict the forwarding probability from the source to the destination. However, it is costly to obtain this dynamic information. In this paper, we use the internal social feature information to design a heterogeneous community-based routing scheme in OMSNs. The individuals with more common social features contact each other more frequently [17]. Therefore, using the internal social feature information can ensure routing efficiency.

The major advantage to using the internal social feature for routing guidance is the low overhead, which avoids the cost of the information collection process. In [17], the authors introduced a hypercube-based social-aware routing approach, which forms an m-dimensional hypercube, in which two nodes are connected if and only if they differ in one social feature. Then, the routing scheme becomes a hypercube-based feature matching process, which resolves the social feature distance step-by-step. In this paper, we consider the routing problem in a single-copy scenario. Therefore, determining the priorities of the social feature dimensions becomes a key challenge. In this paper, we use the transition probability to measure the priorities of the social feature dimensions. Transition probability is the average contact probability of two groups of nodes in a social feature dimension. For example, the transition probability between male and female is 0.5 in social feature dimension: *gender*.

Initially, the source node has a different dimension set (D), which determines the different social feature dimensions to the destination. The source will extract a *forwarding set* (F, $F \subseteq D$) based on the transition probabilities from the message holder to the destination via the relay dimensions, which is a set of next relay dimensions that can reduce the expected delivery delay. After the forwarding, the different dimension set will update by deleting the resolved dimension. Then, the new message holder will do the 2-hop routing recursively until it reaches the destination group.

The major contributions of our work are as follows:

- We use the internal social features and consider the routing problem in a heterogeneous social feature space.
- We convert the social-aware routing problem into a iterative 2-hop routing problem.
- We present an optimal forwarding set selection mechanism for routing guidance.
- We extend the single-copy community-based scheme into a multi-copy scheme.
- We evaluate the proposed scheme in both synthetic and real traces. The simulation results show the competitive performance of our proposed scheme in OMSNs.

The remainder of this paper is organized as follows. Section II reviews the recent related work. Section III shows the overview of our work. Section IV presents the single-copy-based iterative 2-hop routing approach. Section V discusses the extension of our work. Section VI focuses on the simulation and evaluation. We summarize the work in Section VII.

II. Related Work

Depending on the number of copies of a single message that may coexist in the network, there are two categories of

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routing schemes: *single-copy* and *multiple-copy* approaches. In the opportunistic mobile social network research community, most of the existing routing schemes are based on the multiple-copy scenario. The simplest option is to use epidemic algorithm [15]. In order to control the copies of the packet, most of the extended methods taking advantage of the history of past encounters is implemented. In [12, 13], two multi-copy routing schemes, spray-and-wait and spray-and-focus, are proposed. The source spray-and-wait is the same as 2-hop routing. Binary spray always halves the number of copies at each spray; it allows multi-hop unless the current node has one copy left. Spray-and-focus goes further to allow multi-hop, even when there is only one copy. Multi-hop is based on a quality metric like delegation forwarding [4]. However, it is difficult to control the number of copies in the multiple-copy schemes. In this paper, we present a single-copy scheme, which reduces the overhead.

Many social-aware approaches have been proposed [1, 2, 5, 9, 14, 16, 17]. In the SimBet routing scheme, Daly and Haahr [3] proposed the routing scheme based on the social network characterizing information: similarity and ego-centric betweenness centrality. In BUBBLE Rap [7], Hui et al. used human mobility information, in terms of social structures, in the design of forwarding algorithms for pocket switched networks. Gao et al. exploited node centrality and social community structures, and designed multicast protocol in DTNs [5]. In order to enhance the correctness of the forwarding decision, existing social-aware approaches need to collect sufficient state information, including mobility and contact information. Although some predictive models [6, 8] can be applied to obtain such information, it is still very costly, especially in a dynamic network such as an OMSN. In this paper, we use the internal social feature to guide the routing process, which is easy to obtain.

III. Overview

In this section, we first present the system model of the proposed OMSN routing approach and the motivation of our work. Then, the big picture of this paper will be discussed.

A. System Model

In OMSNs, the opportunistic contacts are described by network contact graph $G(V, E)$, where V is the set of mobile nodes in the network, and E is the set of links, with each link in E representing the opportunistic contacts between pairwise nodes. In this paper, each mobile node can be represented by a social feature profile, a representation of her/his social features within a feature space. The social features represent either physical features, such as gender, or logical ones, such as a membership in a social group.

B. Motivation

In most of the existing routing approaches in DTNs, the dynamic contact information is collected to assist the forwarding decision, which considers the routing problem in an unstructured and mobile contact space. To collect this contact information is costly and unpredictable.

In OMSNs, when a mobile node determines whether to forward a message to an encountered node, most recent social-aware routing schemes compare the community structure and/or the social properties, such as centrality, of these two contacting nodes. However, the community structure needs the global view of the whole network or sub-network, which is impossible in OMSNs. Although the centrality of the mobile nodes may be measured by local information, it may also have high overhead to maintain this information.

In this paper, we use the internal social feature information for routing guidance. The social feature information is easy to obtain, and is static over a long period. At the same time, the social feature information can demonstrate the social behavior and interesting aspects of the mobile nodes.

Since we consider a single-copy model in OMSNs, choosing an accurate relay node becomes the most important thing in a routing scheme. In this paper, we consider the routing problem in a heterogeneous social feature dimension. If there are a large number of communities in one dimension, (in other words, if there are a large number of different distinct values in this social feature,) the contact probability between the message holder and the destination community members (message holder and destination node are in different communities) will be small. Therefore, the social feature dimension with a large number of communities is considered to have higher priority.

C. The Big Picture

We consider a generic scenario for opportunistic communication, in which a node with a message independently determines whether to forward a message to another node when they opportunistically contact each other. The goal of our forwarding decision is to make sure the message can be forwarded to the destination in a small number of relays with small delivery delay.

In this paper, we consider the routing problem to be a social feature distance resolving process. In each step, a 2-hop routing approach is considered. As shown in Fig. 1, the message holder considers the *link-state* graph. The first hop of the 2-hop routing scheme is a link form the message holder to the relay node with the same social feature value in this social feature dimension d_i. Another hop is a virtual link from this relay node to the destination group. Here, the destination group means the nodes with exactly the same values of social features in all dimensions. Then, we present an optimal forwarding set selection mechanism, which selects a set of social features that can be resolved in this step. Our basic idea of the optimal forwarding set selection mechanism is calculating the *transition probability* of the 2-hop routing scheme, and extracting the optimal set of social features which can achieve the smallest message forwarding delay.

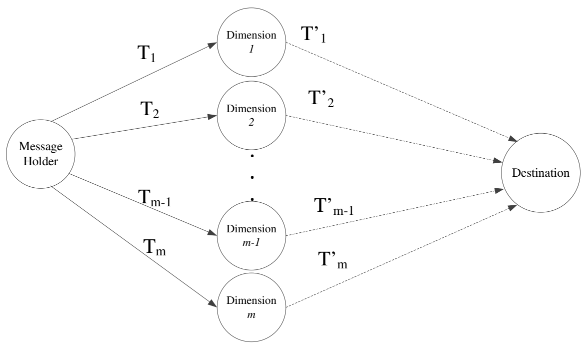

Fig. 1. An illustration of Link-state graph.

IV. Recursive 2-Hop Routing

A. Link-State Graph

Our proposed community-based routing approach is a social feature difference resolving process, which means that the social distance between the source and destination will be resolved dimension by dimension. The major challenge is the priorities of resolving social feature dimensions.

Here, we assume that each node has the information of the number of communities in each social feature dimension. We also assume that the size of each community in each social feature dimension submits to uniform distribution. We assume that the inter-contact time between two nodes in different communities in dimension i follows the exponential distribution. Here, we define *transition probability* (T_i) in dimension d_i as the parameter of the contact probability between two nodes in different communities in dimension i, which can be represented by the following equation: $T_i = \frac{1}{f_i}$, where f_i is the number of different distinct values in social feature dimension i. For example, the transition probability between male and female in the social feature dimension – gender, is 0.5.

As shown in Fig. 1, considering a two-hop routing, the first hop from the message holder to a relay node in social feature dimension d_i, has a transition probability T_i. The second hop is a virtual hop from the relay node to the final destination, which can be estimated as

$$T'_i = (|D| - 1)! \times \prod_{j \in D - d_i} T_j, \tag{1}$$

where D is the dimension difference set between the message holder and the destination. $|D|$ is the size of the set D. $(|D| - 1)!$ shows the possible combination of the sequences. Based on this information, we can determine a forwarding set of the first hop, of which we will discuss the details in the next subsection. Then for the virtual hop, we divide the forwarding path again into a 2-hop routing, and repeat the same process for dimension set $D - d_i$.

B. Forwarding Set Selection

The objective of our proposed single-copy routing protocol is to achieve minimum expected delay from the source to the destination. Our heterogeneous community-based routing approach is an opportunistic routing approach, in which the message holder only forwards the message to the relay nodes with the same social feature in the forwarding set F. In this part, we will present the details of the forwarding set selection process.

According to the link-state graph (Fig. 1), the probability density function (PDF) of the message delivery delay is

$$h(t) = \sum_{i \in F} \frac{T_i \times T'_i}{\lambda - T'_i} \left[e^{-T'_i t} - e^{-\lambda t} \right], \tag{2}$$

where $\lambda = \sum_{i \in F} T_i$.

Therefore, the expected delay can be calculated as follows:

$$E = \int_0^\infty h(t) \cdot t dt = \frac{1}{\lambda} \left[1 + \sum_{i \in F} \frac{T_i}{T'_i} \right]. \tag{3}$$

In [18], the authors claimed that the optimal forwarding set, F^*, should minimize the corresponding expected delay E.

An optimal greedy algorithm is proposed to select the optimal forwarding set F^*.

Algorithm 1 Forwarding Set Selection

Input: The link-stat graph

Sort all virtual paths by T'_i, $T'_1 > T'_2 > ... > T'_m$;
Set $F = \emptyset$, $E = \infty$, and $j = 1$;
while $T'_j > \frac{1}{E}$ and $j \le m$ **do**
  Add social feature dimension f_j to F;
  Update E according to Eq. 3;
  $j = j + 1$;
end while
return $F^* = F$.

Algorithm 1 illustrates the process of optimal forwarding set selection. The virtual links have a higher probability than $\frac{1}{E}$ will be selected into the forwarding set.

C. Recursive 2-Hop Routing

When we have determined the optimal forwarding set, our forwarding strategy is an opportunistic forwarding approach, which means that the message will be forwarded to the first encountered relay node who has the same social feature in the forwarding set F. After each step, the resolved social feature dimension will be deleted from the dimension set. The social feature resolve process is a recursive 2-hop routing process.

Algorithm 2 Recursive 2-Hop Routing

Input: When a message holder N_i with different dimension set D and forwarding set F_i has a contact with N_j.

if N_j has same value in dimension d_i with the destination && $d_i \in F_i$ **then**
  N_i forwards the message to N_j;
  Update the different dimension set D to $D - d_i$.
end if

Algorithm 2 illustrates the process of the single-copy heterogeneous community-based routing algorithm. If node N_j has same value in social feature dimension d_i with the destination and d_i is in the forwarding set F, N_i will forward the message to N_j. At the same time, the different dimension set will be updated to $D - d_i$. Then, we divide the following forwarding path into two hops routing and repeat the same process for the new different dimension set.

After the message is forwarded to a relay with all the same social features as the destination, the relay terminates the forwarding process and waits to meet with the destination.

D. Shortcuts

In the previous parts, the social feature distance is assumed to be resolved one in each step. Here, we introduce the concept of *shortcuts*. If there are multiple social feature dimensions in the forwarding set, we can extend the basic scheme by shortcuts, which means that more than one social feature distance can be resolved at one step. In other words, if the encountered node has more than one social features, which are the same as those of the destination, and these social feature dimensions are in the forwarding set of the message holder, the message will be forwarded to this reply node. At the same time, these social feature dimensions will be deleted from the dimension forwarding set.

The only difference between the shortcuts and without shortcuts is the forwarding dimension updating process. In other word, in the shortcuts scheme, after message forwarding, the dimension set will be updated to $D - \mathbb{D}_j \bigcap F_i$.

Algorithm 3 illustrates the whole process of the routing scheme with shortcuts.

Algorithm 3 Single-copy Heterogeneous Community-based Routing with Shortcuts

```
/* When a message holder N_i with different dimension
   set D and forwarding set F_i has a contact with N_j. */
/* The dimension set N_j is 𝔻_j. */
if (𝔻_j ⋂ F_i) ≠ ∅ then
    N_i forwards the message to N_j;
    Update the dimension set D to D − 𝔻_j ⋂ F_i.
end if
```

V. Extension

In the previous sections, we discussed the single-copy community-based scheme, which is extended to the multi-copy scheme in this section. The source node will partition the message copies to its encountered nodes. In an m-dimensional space, we assume that there are C copies of a message created by the source node. Each qualified relay node will receive one copy. In order to increase the delivery efficiency, the forwarding paths of these C copies should be C node-disjoint paths from the source to the destination. The node-disjointness means that these C paths are parallel without overlap, which can control the overhead, and at the same time, increase the efficiency. Suppose that the source and the destination differ in k dimensions $D = \{1, 2, ..., k\}$. Here, we assume that $C < k$.

In this section, we introduce a greedy algorithm to select the C node-disjoint paths. First of all, according to Eq. 3, we can estimate the expected delay from source to the destination based on the transition probability (T) of each link for all possible sequences with path length k. Then, from all possible sequences, we select the best sequence with the smallest expected delay. After that, we will use this sequence to find C paths for the message copy forwarding. In order to achieve node-disjointness of these C paths, the concept of *coordinate sequence* is introduced.

$D^0 : \langle 1, 2, ..., k \rangle$ is defined as the *coordinate sequence* from a given D. D^0 determines how a path is constructed based on the resolution order of dimension differences given in D. D^i is defined as i circular left shifts of D^0. In fact, D^0 can be any permutation of D. Then, k sequences, $D^0, D^1, ..., D^{k-1}$, will create k node-disjoint shortest paths from D:

- *Path* 1 generated by D^0: $\langle 1, 2, 3, ..., k \rangle$;
- *Path* 2 generated by D^1: $\langle 2, 3, 4, ..., k, 1 \rangle$;
- *Path* 3 generated by D^2: $\langle 3, 4, 5, ..., k, 1, 2 \rangle$;

  ......
- *Path* k generated by D^{k-1}: $\langle k, 1, 2, ..., k-2, k-1 \rangle$.

In our forwarding path selection protocol, D^0 is the best sequence we discussed above. Once we have k coordinate sequence paths, we need to select the best C paths since we only have C copies of message. The C best paths selection process is the smallest expected delay paths selection process, which is the same as we discussed above for best sequence selection.

This multiple-copy scheme is similar to hypercube routing in that the source node will choose the best C 1-hop neighbors as the relay nodes. Then, each relay node will follow the path sequence, forwarding the message to the destination.

The aforementioned algorithm is like selecting best C paths out of k possible solutions, which is linear, if $C \leq k/\log k$ by using a heap, or $\Theta(k \log k)$, if $C > k/\log k$ by using sorting.

VI. Simulation

A. Simulation Setup

We evaluate our proposed scheme in two real traces: Infocom 2006 trace [11], which is a conference contact trace, and MIT reality mining trace [10], which records the contacts between the participants on the campus. In Infocom 2006 trace, we extract 6 social features from the original dataset: affiliation, city, nationality, language, country, and position. We also extract 6 social features from MIT reality mining trace: neighborhood, daily commute, hangouts, working hours, affiliation, and research group.

For the synthetic trace, we create a 100-node network with 8 social features. There are 2, 3, 4, 5, 6, 7, 8, and 16 distinct values for each social feature, respectively. Each node will randomly assign the social feature vector. Suppose that the degree distribution follows power-law distribution. Since, we know that mobile nodes come in contact with each other more frequently if they have more social features in common; the contact frequency is proportional to the social feature distance between each pairwise set of nodes.

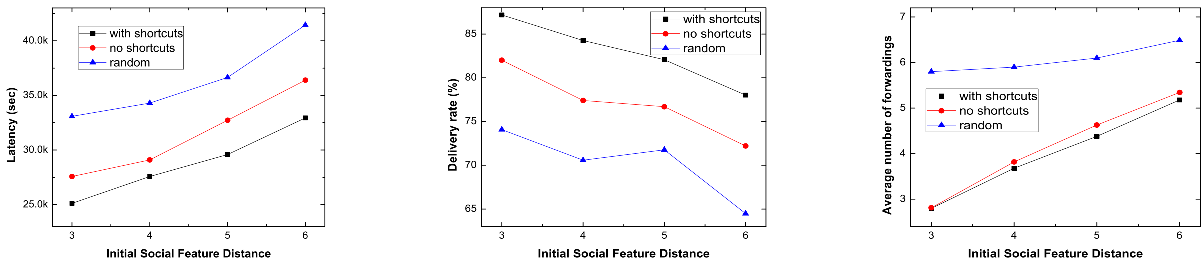

Fig. 2. Simulation results in the Infocom trace.

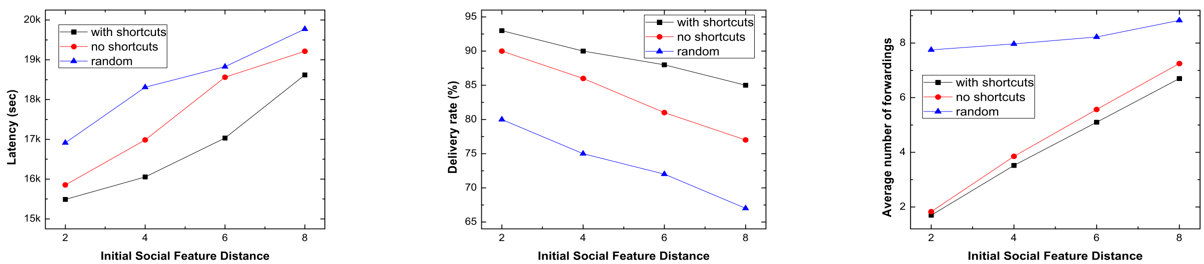

Fig. 3. Simulation results in the synthetic trace.

The simulation is grouped into the following two categories: 1) **Efficiency evaluation**: we compare our proposed scheme in both the shortcuts and no shortcuts versions, with the random forwarding scheme, in both real and synthetic traces. 2) **Comparison to the state-of-art scheme**: we compare the performance between our proposed scheme and SimBet.

The comparison schemes are listed as follows: 1) **Random forwarding**: forwarding the message to any encountered node until it reaches the destination. 2) **SimBet** [3]: this is a social-aware routing approach, which leverages the *similarity* and *ego-centric betweenness centrality* to enhance the forwarding decision. Here, the similarity presents the number of common neighbors between the current node and the destination node. If each node has local information of neighbors and neighbors' neighbors, ego-centric betweenness centrality measures how much a node connects neighbors that are not directly connected themselves. Here, we also change the number of initial copies the source node generates in order to see the performance.

In the simulation, we compare three different parameters: latency, delivery rate, and number of forwardings.

B. Simulation Results

1) **Efficiency evaluation:** here, we compare the performance of our proposed scheme to the random forwarding scheme with varying initial social feature distances between the source and destination. In two real traces, we set the initial social feature distances between the source and destination to be 3, 4, 5, and 6. In the synthetic trace, the initial social feature distances between the source and destination are set to be 2, 4, 6, and 8.

In both real and synthetic traces, we can see that our proposed scheme has better performance than the random forwarding scheme, as shown in Figs. 2 and 3. In the random forwarding scheme, the message will be forwarded to any encountered node. Therefore, the number of forwardings is increased dramatically. However, this scheme cannot reduce the latency in its high cost manner. Since the message forwarding is purely random, it is with high probability that the message may reach a dead end in the random forwarding scheme. In the Infocom 2006 trace, our scheme can be reduced by about 24% delivery time, and increase by about 19% delivery rate, compared with the random forwarding scheme. The MIT reality mining and synthetic traces show the same results.

By using the shortcuts in our proposed scheme, the efficiency of the routing approach can also be improved. In the Infocom trace, the number of forwardings is reduced by about 10%, by using the shortcuts in our scheme. At the same time, the latency is reduced and delivery rate is increased. The results in MIT reality mining and synthetic traces confirm the efficiency of the shortcuts scheme.

2) **Comparison with SimBet:** ss shown in Figs. 4 and 5, our scheme performs much better than the SimBet approach with one copy. When the initial number of copies increases in the SimBet scheme, its latency declines and its delivery rate increases. It has a similar latency and delivery rate as our single-copy scheme, when the initial number of copies increases to 3. But, it has much higher cost than our scheme; the real and synthetic traces show the same trends. Compared with the existing social-aware routing scheme – SimBet, our scheme performs better when there is a limited initial number of copies. SimBet needs to collect the social structure information, which is very costly. Therefore, our approach is more suitable than SimBet in OMSNs.

C. Summary of Simulation

Our simulation results show the efficiency of our proposed heterogeneous community-based routing scheme. The random forwarding approach forwards the message to any encounters, which may pull the message away from the destination. Also,

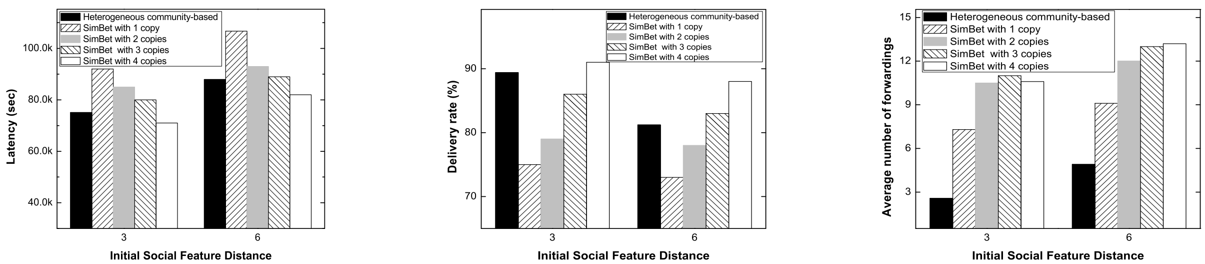

Fig. 4. Comparison with SimBet scheme in the MIT reality trace.

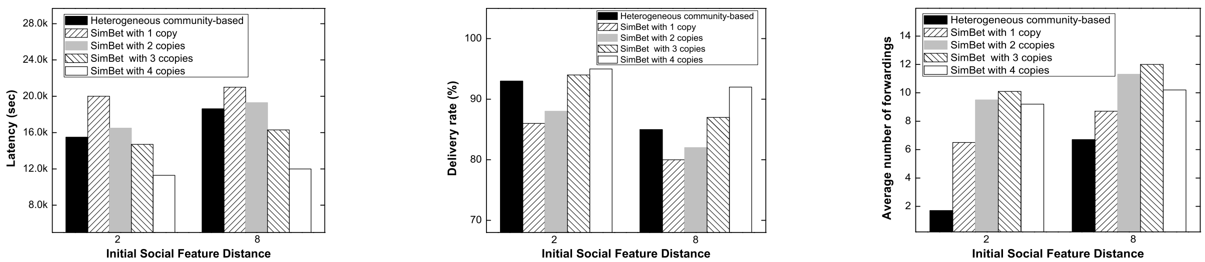

Fig. 5. Comparison with SimBet scheme in the synthetic trace.

it has a higher probability of entering a dead end. Using the internal social feature information for routing guidance can increase the contact probability with the destination, and can reduce the number of forwardings and latency; at the same time, it can increase the delivery rate. Shortcuts enhance the robustness of our approach. Compared with the existing social-aware routing scheme – SimBet, our scheme performs better when there is a limited initial number of copies. SimBet needs to collect the social structure information, which is very costly. Therefore, our approach is more suitable than SimBet in OMSNs.

VII. Conclusion

In this paper, we propose a single-copy heterogeneous community-based routing scheme, which is based on the internal social feature information. The social feature distance between the source and destination is resolved by a recursive 2-hop routing process. In each step, the message holder will extract an optimal forwarding set, including the social feature dimensions that can reduce the expected delivery delay. The optimal forwarding set is determined by the transition probability through the distance of the social feature spaces to the destination. Then, we introduce a shortcuts policy to improve the efficiency of our approach. Simulation results confirm the efficiency of our approach when compared with the state-of-art schemes, in both real and synthetic traces. We believe that the social features will play an important role in routing in opportunistic mobile social networks. Our future work is to design an opportunistic mobile social network system by using smartphones to validate our proposed scheme.

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