Energy Efficient Social Routing Framework for Mobile Social Sensing Networks

Fan Li  
*School of Computer Science, Beijing Institute of Technology, Beijing 100081, China.*

Chenfei Tian  
*School of Computer Science, Beijing Institute of Technology, Beijing 100081, China.*

Ting Li  
*the Department of Computer Science, the University of North Carolina at Charlotte, 9201 University City Blvd., Charlotte, NC 28223, USA.*

Yu Wang  
*the Department of Computer Science, the University of North Carolina at Charlotte, 9201 University City Blvd., Charlotte, NC 28223, USA.*

Follow this and additional works at: [https://tsinghuauniversitypress.researchcommons.org/tsinghua-science-and-technology](https://tsinghuauniversitypress.researchcommons.org/tsinghua-science-and-technology)

Part of the Computer Sciences Commons, and the Electrical and Computer Engineering Commons

**Recommended Citation**

Fan Li, Chenfei Tian, Ting Li et al. Energy Efficient Social Routing Framework for Mobile Social Sensing Networks. *Tsinghua Science and Technology* 2016, 21(4): 363-373.

This Research Article is brought to you for free and open access by Tsinghua University Press: Journals Publishing. It has been accepted for inclusion in Tsinghua Science and Technology by an authorized editor of Tsinghua University Press: Journals Publishing.
Energy Efficient Social Routing Framework for Mobile Social Sensing Networks

Fan Li*, Chenfei Tian, Ting Li, and Yu Wang

Abstract: Mobile social sensing network is one kind of emerging networks in which sensing tasks are performed by mobile users and sensing data are shared and collected by leveraging the intermittent inter-contacts among mobile users. Traditional ad hoc routing protocols are inapplicable or perform poorly for data collection or data sharing in such mobile social networks because nodes are seldom fully connected. In recent years, many routing protocols (especially social-based routing) are proposed to improve the delivery ratio in mobile social networks, but most of them do not consider the load of nodes thus may lead to unbalanced energy consumption among nodes. In this paper, we propose a simple Energy Efficient framework for Social-based Routing (EE-SR) in mobile social sensing networks to balance the load of nodes while maintaining the delivery ratio within an acceptable range by limiting the chances of forwarding in traditional social-based routing. Furthermore, we also propose an improved version of EE-SR to dynamically adjust the controlling parameter. Simulation results on real-life mobile traces demonstrate the efficiency of our proposed framework.

Key words: energy efficient; social-based routing; delay tolerant networks; mobile social sensing networks

1 Introduction

The appearance of smartphones with various sensing capabilities and increasing popularity of mobile applications have enabled a new sensing paradigm, mobile sensing[1, 2], for collecting and sharing sensing data from surrounding environment. One of the challenges faced by mobile sensing is how to efficiently collect the mobile data beyond the existing capacity of 4G networks. One possible solution is to leverage the occasional device-to-device contact opportunities among mobile devices to deliver sensing data rather than using the fixed network infrastructure[3–7].

Leveraging the node mobility and opportunistic relay for packet delivery is a common technique developed for Delay Tolerant Networks (DTNs)[8, 9] or mobile opportunistic networks[10, 11]. In these networks, the end-to-end path does not exist all the time from the current node to the destination node due to the frequent network partitions. This makes routing tasks more challenging than those in traditional wireless networks. The simplest solution is Epidemic[12], in which whenever a node carrying a message encounters with another node, it copies a replica of the message and forwards the replica to the encountered node. However, such flooding-based solution also causes relatively high network overhead. To overcome the shortage of Epidemic routing, many routing protocols limit the number of replicas, such as Spray and Wait[13]. Generally, the delivery ratio of flooding-based strategies is relevant high, but the heavy load of nodes may cause serious congestions or energy issues. Existing DTN routing protocols adopt “store-carry-forward”, where if there is no connection available, the current node stores
and carries the message, and then makes a decision whether to forward the message when it encounters another node. For example, PRoPHET\cite{14} predicts the delivery probability in the future network based on historical contacts, and then decides whether to forward the message. Fresh\cite{15} forwards packets to the encountered node if it meets the destination node more recently than the current node does. Greedy-Total\cite{16} forwards messages to the encountered node if it has a higher contact frequency to all other nodes than the current node does.

To further improve the prediction of future encounters, many social-based routing protocols\cite{9} are proposed. Mobile devices are used and carried by human beings, so the behaviors of the network can be better characterized by their social attributes. Different social-based routing methods use various social attributes. A simple way is using degree centrality in delegation forwarding\cite{17}, where the current node only forwards a message to nodes with degree centrality greater than any seen so far for this message. Here, the degree centrality of a node is the number of its neighbors in social graph which represents its social activeness. SimBet\cite{18} is another representative social-based routing protocol. When current node encounters another node, the message in SimBet is more likely to be forwarded to the node with higher social centrality and more similar with the destination node. Label\cite{19} and Group\cite{20} try to forward the message to the node whose group is the same with the destination node. Bubble Rap\cite{11} forwards the message with two phases: a bubble-up phase based on global centrality and a bubble-up phase based on local centrality.

All of the above routing protocols focus on improving the delivery ratio without considering the energy usages of the mobile nodes, which could significantly affect the life-time of mobile devices. In this paper, we propose an Energy Efficient framework for Social-based Routing (EE-SR) in mobile social networks which aims to reduce the load of nodes in social-based routing by limiting the chances of forwarding at each encounters. We also propose an improved version (EE-SR-I) to dynamically adjust the controlling parameter so that the delivery ratio can still be at certain level. The performance of our proposed methods are evaluated through simulations over real-life data traces and compared with other existing social-based routing protocols.

The rest of this paper is organized as follows: Section 2 reviews existing social-based routing methods for DTNs and mobile social networks. Section 3 presents the detailed design of the proposed EE-SR and EE-SR-I. Section 4 describes simulation results and Section 5 concludes the paper. A preliminary version of this paper was appeared in Ref. [21].

2 Related Work

In the previous studies, many routing protocols have been proposed for DTNs\cite{11, 13, 18, 22}, mobile social networks\cite{20, 23, 24}, mobile D2D offloading\cite{3–5}, and mobile crowd sensing\cite{6, 7}. They can be roughly divided into two categories: store-carry-forward strategy and flooding-based strategy\cite{24}. For the store-carry-forward strategy, the current node stores and carries the message, and makes a forwarding decision when encounters another node. For the flooding-based strategy, there will be multiple copies of each message in the whole network, such as Epidemic\cite{12}. Though the delivery ratio of flooding-based method is usually high, the multi-copy strategy may greatly increase the loads of nodes and cause serious congestions. Since we focus on social-based routing in this paper, we now briefly review the existing social-based routing methods.

Recently, social-based routing has attracted a lot of attention since most mobile devices (such as smart phones) are now used and carried by people, and the network behaviors can be better characterized by their social attributes. Social-based routing methods aim to carefully choose the relay nodes by choosing a good social metric to measure the capability of nodes to deliver the message to the destination. During any encounter, if the encountered node has higher social metric than the current node, the current node will forward its message copy to the encountered node. For example, SimBet\cite{18} uses betweenness centrality and the similarity with destination node as the social metric. Bubble Rap\cite{11} uses global centrality and local centrality to decide whether to forward the message. Gao et al.\cite{22} also utilized centrality (defined by a cumulative contact probability) and community as the social metrics to design social-based multicast routing protocols. Friendship\cite{23} defines its friendship community as the set of nodes having close friendship (defined by using contact probability) with itself either directly or indirectly. SEBAR\cite{24} introduces social energy (generated by the encounters and shared by communities) to quantify the social ability of forwarding messages to other nodes, which consists
of two parts: the reserved energy generated by itself from direct node encounters with other nodes and the reallocated energy gained from its communities.

In this paper, we are committed to reduce the load of nodes in social-based mobile networks. It is well-known that the energy of mobile devices is very precious due to the limited capacity of battery. When some nodes run out of energy, it may have a great impact on the performance of the network, especially for sparse mobile networks. Existing social-based routing methods usually choose a node with higher social metric to be the next relay, and they do not consider the energy consumption. In order to save node energy in social-based mobile networks, we aim to minimize the number of forwards for message transmission while maintaining acceptable delivery ratio.

3 General Energy Efficient Framework for Social-Based Routing

In this section, we introduce our proposed EE-SR in mobile social networks. The aim of EE-SR is to save the energy consumption of the whole network by limiting the number of message forwardings. Recall that the message will not be forwarded to the encountered node unless the current node has lower social metric than the encountered node. Here, Social Metric ($SM$) could be any existing social metrics, such as degree centrality in Refs. [25, 26], between centrality and similarity in $SimBe$[18], friendship in Friendship[23], and social energy in $SEBAR$[24]. Our proposed EE-SR is a general framework to reduce the load of each node, and it can be applied to any existing social-based routing methods as long as they use social metric per node for relay selection and forwarding decision.

To calculate the social metric value of a node, a social graph is needed to describe the social relationships among nodes. Usually such a social graph is generated from historical contacts[27]. Assume that $V = \{v_1, v_2, \ldots, v_n\}$ is the set of nodes in the network. Each node can send and receive messages when it encounters another node (the physical distance between them is less than the transmission range of their radios). To generate the social graph, we set a threshold on contact frequency to judge whether there is a close relationship between two nodes in the network. If the number of contact times between two nodes is larger than or equal to the threshold, there is an edge between these two nodes in the generated social graph. The generated social graph contains all nodes and their relations. Given this graph, a variety of social metrics can be calculated and used by our routing algorithms. We use $SM(v_i)$ to denote the social metric of node $v_i$.

3.1 EE-SR: Basic version

In traditional social-based routing protocols, the messages are forwarded to the encountered nodes with larger social metrics. This may help to achieve higher delivery ratios, but nodes with large social metric values may run out of battery soon due to their heavy load. Therefore, we consider to improve the traditional social-based routing methods by enlarging the social metric of current node $v_i$ to amp_ratio times of the original value. Here, amp_ratio $\geq 1$. Thus, it becomes more difficult for the current node to transfer its message because the encountering node needs to have amp_ratio times higher social metric value than that of current node to be chosen as a relay. By doing so, the number of forwardings in the network will be reduced. Naturally, the delivery ratio of the new method decreases, thus we dynamically adjust the amplification ratio amp_ratio based on the Time To Live (TTL) of the packet to avoid low delivery ratio. TTL of the packet indicates whether the packet is out-of-dated and when the message should be discarded. At the beginning, the TTL value of a message is set to a constant TTL0. After each hop, the value of TTL will minus one. When TTL is reduced to zero, the message will be discarded.

In EE-SR, the forwarding happens only when the social metric of the encountered node is amp_ratio times larger than that of the current node. The basic idea of dynamically adjusting amp_ratio is as follows. At the beginning, when TTL is large, EE-SR puts minimizing the load of nodes as its first priority, thus the value of amp_ratio is set high. However, after several hops, when TTL is reduced to a small value, which means the packet will be discarded soon, EE-SR puts improving the delivery ratio as its first priority, so the value of amp_ratio should be set small. Therefore, we set

$$amp\_ratio = 1 + \frac{ttl}{TTL_0} \cdot \theta,$$

where $\theta$ is a predefined constant used to determine the initial value of amp_ratio, and TTL0 and ttl are the initial TTL value and the current TTL value of the message, respectively. Note that EE-SR regresses to the traditional social-based routing when amp_ratio = 1. Algorithm 1 shows the detailed description of EE-SR.
Algorithm 1 EE-SR: Basic Version

Node \( v_i \) with message \( M \) meets \( v_j \) which does not hold \( M \).

1. if \( v_j \) is the destination then
2. \( v_j \) forwards \( M \) to \( v_j \)
3. else
4. \( \text{amp\_ratio} \leftarrow 1 + \frac{\text{ttl}}{\text{TTL}_0} \cdot \theta \)
5. if \( \text{SM} (v_j) \cdot \text{amp\_ratio} \leq \text{SM} (v_j) \) then
6. \( v_j \) forwards \( M \) to \( v_j \)
7. \( \text{ttl} \leftarrow \text{ttl} - 1 \)
8. else
9. \( v_j \) holds the \( M \) and waits for the next encounter

end if
end if

Compared with traditional social-based routing methods, EE-SR aims to reduce the load of nodes. We illustrate an example in Fig. 1, which shows the connectivity among nodes from \( T = 0 \) to 3. The number inside each node represents its \( \text{SM} \) value. Assume that node \( v_1 \) has a message destined to \( v_5 \). The message will go through \( v_2, v_3, \) and \( v_4 \) and reach \( v_5 \) eventually by traditional social-based routing. Thus the loads of each node are 1, 2, 2, 2, and 1, respectively. Here, we assume that every time when a message is forwarded from one node to another node, the load of both involving nodes will plus one. In this example, increase ratio \( \theta = 0.5 \) and \( \text{TTL}_0 = 5 \). In EE-SR, \( v_1 \) will not forward the message to \( v_2 \) at \( T = 0 \) because \( \text{SM}(v_2) \) is not 1.5 times larger than or equal to \( \text{SM}(v_1) \).

The message will be forwarded from \( v_1 \) to \( v_3 \) at \( T = 1 \) because \( \text{SM}(v_3) \) is 1.5 times larger than \( \text{SM}(v_1) \).

At \( T = 2 \), the message will be forwarded to \( v_4 \) because \( \text{SM}(v_4) \) is 1.4 times larger than \( \text{SM}(v_3) \). Here, \( \text{amp\_ratio} = 1 + \frac{4}{5} \times 0.5 = 1.4 \). At \( T = 3 \), the message will be forwarded to the destination node \( v_5 \). Therefore, the packet will go through \( v_3 \) and \( v_4 \) and reach \( v_5 \) with EE-SR. The loads of each node are 1, 0, 2, 2, and 1, respectively. Overall, the load of \( v_2 \) is reduced by EE-SR in this example. Our simulation results in Section 4 confirm that EE-SR can reduce the loads of nodes in mobile social networks.

3.2 EE-SR-I: Improved version

If the \( \text{SM} \) value of source node is large, it might be difficult to find a node whose \( \text{SM} \) value is \( \text{amp\_ratio} \) times larger than itself except for the destination node. This phenomena could have a great impact on delivery ratio. To prevent it from happening, we design an additional mechanism to further dynamically adjust \( \text{amp\_ratio} \) based on past encounters. When a node encounters more than \( K \) nodes whose \( \text{SM} \) values are larger than itself, but still does not forward the message (since the \( \text{SM} \) values of the encountered nodes are not greater enough than \( \text{amp\_ratio} \) times of the current node), then our method slowly relaxes the forwarding condition by gradually decreasing the value of \( \text{amp\_ratio} \). In this improved version (denoted by EE-SR-I), the amplification ratio \( \text{amp\_ratio} \) is dynamically adjusted by: both \( \text{TTL} \) of the packet and the number of encounter nodes (i.e., \( \text{node\_counter} \)) whose \( \text{SM} \) values are larger than itself, but still does not forward the message (since the \( \text{SM} \) values of the encountered nodes are not greater enough than \( \text{amp\_ratio} \) times of that). Here, \( K \) is the pre-defined threshold for \( \text{node\_counter} \). Algorithm 2 shows the detailed method.

It should be emphasized that both EE-SR and EE-SR-I are general frameworks for social-based routing in mobile networks. That is to say, any existing social-based routing methods could use our proposed EE-SR or EE-SR-I to reduce the load of each node. And it is very easy to realize our framework on different social-based routing methods, the only modification is to replace the general \( \text{SM} \) of nodes in the algorithm with a specific social metric, such as SimBet utility or degree centrality. In the next section, we will demonstrate our proposed framework on both SimBet routing and routing method based on degree centrality.

![Fig. 1 An example of EE-SR.](image-url)
4 Simulations

We have conducted extensive simulation experiments over real-life mobile traces to evaluate our proposed EE-SR and EE-SR-I frameworks. In our simulations, we first use the SimBet utility value\textsuperscript{[18]} as our SM value for our proposed EE-SR and EE-SR-I, we call them EE-SimBet and EE-SimBet-I, respectively, in this section. Recall that in SimBet routing\textsuperscript{[18]}, the message is more likely to be forwarded to the node with high social centrality and more similar with the destination node. The SimBet utility value basically is a weighted value of the centrality and the similarity with the destination node. We compare EE-SimBet and EE-SimBet-I with the following existing routing methods.

- **Epidemic**\textsuperscript{[12]}: During any encountering, the node copies a replica of the packet and forwards it to any encountered nodes.
- **SimBet**\textsuperscript{[18]}: The packet is only forwarded from node \(v_i\) to node \(v_j\) if the SimBet utility of node \(v_j\) is larger than that of node \(v_i\).
- **FRESH**\textsuperscript{[15]}: The packet is only forwarded from node \(v_i\) to node \(v_j\) if \(v_j\) has met the destination more recently than \(v_i\) does.
- **Greedy-Total**\textsuperscript{[16]}: The packet is only forwarded from \(v_i\) to \(v_j\) if \(v_j\) has a higher contact frequency to all other nodes than \(v_i\) does.

In all experiments, we compare the performance of each routing method using the following routing metrics.

- **Delivery Ratio**: the average percentage of the successfully delivered packets from the sources to the destinations.
- **Maximum Load**: the highest load of all nodes within a certain period of time.
- **Average Load**: the average load of all nodes within a certain period of time.
- **Average Hops**: the average number of hops during each successful delivery from the sources to the destinations.
- **Average Forwards**: the average number of forwarding times during each delivery (not only limited to successful delivery) from the source to the destination.
- **Average Delay**: the average duration of successfully delivered packets from the sources to the destinations.

We choose InfoCom 2006 trace data\textsuperscript{[28]} to simulate the mobile social network environment. This trace data includes connections among 78 mobile iMote Bluetooth nodes carried by participants of a student workshop for four days during InfoCom 2006 in Barcelona, Spain. Each record in the data set contains information about the ID of the device who recorded the sightings and the device who was seen. It also contains the starting time and the ending time for a certain contact. The contact information from the first 62 hours is treated as historical data to generate the social graph, then the performances of routing tasks are evaluated over the remaining 30 hours. Each node tries to send a packet to all other nodes. Therefore, we have \(78 \times 77 = 6006\) source-destination pairs and routing tasks. Here, we consider single-copy version of all routing methods, where only one copy is allowed within the network for any messages. To generate the social graph, we add an edge between two nodes if their total contact time is greater than one, which is the same as the setting in SimBet. Table 1 summarizes all parameters used in EE-SimBet and EE-SimBet-I.

4.1 Simulation results of EE-SimBet

Figure 2 demonstrates the performance comparison among EE-SimBet and other four existing routing methods. As Figs. 2a shows, Epidemic has the highest delivery ratio because it offers the upper bound of the delivery ratio that any routing protocol can achieve.

---

**Algorithm 2 EE-SR-I: Improved Version**

Node \(v_i\) with message \(M\) meets \(v_j\) which does not hold \(M\).

1. if \(v_j\) is the destination then
2. \(v_j\) forwards \(M\) to \(v_j\)
3. else
4. if \(SM(v_i) < SM(v_j)\) then
5. \(\text{node\_counter} \leftarrow \text{node\_counter} + 1\)
6. if \(\text{node\_counter} \geq K\) then
7. \(\text{amp\_ratio} \leftarrow 1 + \frac{\text{ttl}}{\text{TTL}_0} \cdot \frac{1}{\text{node\_counter} - K + 1}\)
8. else
9. \(\text{amp\_ratio} \leftarrow 1 + \frac{\text{ttl}}{\text{TTL}_0} \cdot \theta\)
10. end if
11. end if
12. if \(\text{amp\_ratio} \leq SM(v_j)\) then
13. \(v_j\) forwards \(M\) to \(v_j\)
14. \(\text{ttl} \leftarrow \text{ttl} - 1\)
15. \(\text{node\_counter} \leftarrow 0\)
16. else
17. \(\text{node}\ v_j\ \text{holds}\ the\ M\ and\ waits\ for\ the\ next\ encounter}\)
18. end if
19. end if
The delivery ratio of EE-SimBet is not very high, since EE-SimBet aims to save the energy by reducing the opportunity of message forwarding. If the $SM$ value of the source node is large, it will be difficult to find an encountering node whose $SM$ value is $amp\text{-ratio}$ times higher than that of the source node. But EE-SimBet has outstanding performance in terms of the maximum and average loads as shown in Figs. 2b and 2c. Note that these two subfigures do not include the results of Epidemic because its maximum load is usually higher than 14000 and its average load is usually higher than 4000. Figures 2e and 2f indicate that average hops and average forwards of EE-SimBet are the smallest among all the methods.

### 4.2 Simulation results of EE-SimBet-I

We then use the improved framework on SimBet (EE-SimBet-I). Figure 3 shows the detailed results. Interestingly, EE-SimBet-I has very close, even slightly better delivery ratio than that of SimBet, and its average delay is at the similar level with that of SimBet. Although the maximum and average loads of EE-SimBet-I increase over time, the load of EE-SimBet-I is still much lower than other algorithms. EE-SimBet-I maintains the smallest numbers of hops and forwards. Compared with EE-SimBet, the improved version has similar delivery ratio with the original social-based routing method while reducing the overall load and numbers of hops and forwards. The standard deviations of the load for different routing methods are reported in Table 2, which demonstrates that EE-SimBet and EE-SimBet-I can also limit the variation range of the load. Overall, EE-SimBet-I can reduce the energy consumption while maintaining the similar or even better delivery ratio with the original social-based routing. By carefully selecting the parameters, EE-SimBet-I can find a balance between load reduction and high delivery ratio.

### 4.3 Impact of parameter $\theta$

In both EE-SR and EE-SR-I, we use a parameter $\theta$ to control the initial value of amplification ratio $amp\text{-ratio}$. To explore the impact of $\theta$ on the simulation results, we set $\theta = 0, 0.25, 0.5, 1, 5, 10$ for EE-SimBet and EE-SimBet-I separately. We select a fixed 10-hour trace data from InfoCom 2006 trace for testing routing performance. Figure 4 shows routing performances

![Fig. 2 Simulation results of EE-SimBet.](image-url)
of EE-SimBet and EE-SimBet-I on different values of $\theta$. Obviously, both EE-SimBet and EE-SimBet-I will degenerate to SimBet when $\theta = 0$. Therefore, their routing performance is exactly the same in this case. With the increase of $\theta$, the amp_ratio increases at the same time, the number of packet forwarding times will decrease according to the EE-SR and EE-SR-I because it’s more difficult to encounter a node whose SimBet utility is amp_ratio times larger than itself. Figures 4e and 4f reflect such a phenomenon. This phenomenon also causes the decrease of delivery ratio because the current node has little chance to forward its packets, as shown in Fig. 4a. Each packet transmission will consume some energy in DTNs, so the average load and maximum load of nodes decrease with the increase of $\theta$ as shown in Figs. 4b and 4c, which is the major purpose of the design of EE-SR and EE-SR-I.

### 4.4 Simulation results over social-based routing with degree centrality

To illustrate that our proposed EE-SR and EE-SR-I are general framework and they can be realized on different social-based routing methods, we now apply them on another simple social-based routing using degree centrality. This kind of social-based method has been used by Refs. [25, 26], where the current node only forwards a message to nodes with degree centrality greater than any seen so far for this message during any encounters. Here, we set the number of neighbors in social graph as the degree centrality of a node. We call this approach Degree routing, and the approaches, after EE-SR and EE-SR-I applied, EE-Degree, and EE-Degree-I, respectively. Except for the social metric, we keep other parameters the same as those shown in Table 1. We also compare EE-Degree and EE-Degree-I with four existing routing methods mentioned before. Figures 5 and 6 show the routing performances.

From Fig. 5, we can see that the delivery ratio of EE-Degree is not very high, whose reason is the same as that of EE-SimBet in Section 4.1. On the other hand, the EE-Degree has outstanding performances in the maximum and average loads as shown in Figs. 5b and 5c, which also proves that our framework can significantly reduce the load of nodes. Figures 5e and 5f
show that EE-Degree has the lowest average hops and forwards among all the routing methods.

Figure 6a shows that the delivery ratio of EE-Degree-I is not higher than Degree routing, but note that its delivery ratio has been improved compared with EE-Degree. EE-Degree-I still has the lowest maximum and average load among all routing methods from Figs. 6b and 6c. Different with EE-Degree, the purpose...
of EE-Degree-I is more likely to find a balance between delivery ratio and energy efficient. Overall, the frameworks of EE-SR and EE-SR-I can be easily applied to Degree routing and enhance its energy efficiency.

5 Conclusion

In this paper, we address how to delivery mobile data efficiently in mobile social sensing networks, where end-to-end paths between any pair of nodes may not exist. Routing in such networks is a challenging problem. Many social-based routing protocols are proposed to improve the delivery ratio over time in such delay tolerant networks, but most of them do not consider the load of nodes. In this paper, we propose an energy efficient framework for social-based routing to reduce the load of nodes in mobile social networks. Our proposed general framework can be easily applied to any existing social-based routing methods which use social metric per node for relay selection. Simulation results over real-life data traces demonstrate the efficiency of our proposed method.

Acknowledgment

The work was partially supported by the National Natural Science Foundation of China (Nos. 61370192, 61432015, 61428203, and 61572347), and the US National Science Foundation (Nos. CNS-1319915 and CNS-1343355).

References

[1] B. Guo, Z. Wang, Z. Yu, Y. Wang, N. Yen, R. Huang, and X. Zhou, Mobile crowd sensing and computing: The review of an emerging human-powered sensing paradigm, ACM Computing Surveys, vol. 48, no. 1, p. 7, 2015.

[2] W. Dai, Y. Wang, Q. Jin, and J. Ma, An integrated incentive framework for mobile crowdsourced sensing, Tsinghua Science and Technology, vol. 21, no. 2, pp. 146–156, 2016.

[3] B. Han, P. Hui, V. S. A. Kumar, M. V. Marathe, J. Shao, and A. Srinivasan, Mobile data offloading through opportunistic communications and social participation, IEEE Trans. on Mobile Computing, vol. 11, no. 5, pp. 821–834, 2012.

[4] Y. Li, M. Qian, D. Jin, P. Hui, Z. Wang, and S. Chen, Multiple mobile data offloading through disruption tolerant networks, IEEE Trans. on Mobile Computing, vol. 13, no. 7, pp. 1579–1596, 2014.

[5] Y. Zhu, C. Zhang, and Y. Wang, Mobile data delivery through opportunistic communications among cellular users: A case study for the D4D challenge, in Proc. of NetMob, 2013.

[6] L. Wang, D. Zhang, and H. Xiong, Effsense: Energy-efficient and cost-effective data uploading in mobile crowdsensing, in Proc. of ACM UbiComp, 2013.

[7] M. Karaliopoulos, O. Telelis, and I. Koutsopoulos, User recruitment for mobile crowdsensing over opportunistic networks, in Proc. of IEEE INFOCOM, 2015.

[8] M. Liu, Y. Yang, and Z. Qin, A survey of routing protocols and simulations in delay-tolerant networks, in Proc. of
International Conference on Wireless Algorithms, Systems, and Applications (WASA 2011), 2011, pp. 243–253.

[9] Y. Zhu, B. Xu, X. Shi, and Y. Wang, A survey of social-based routing in delay tolerant networks: Positive and negative social effects, IEEE Communications Surveys & Tutorials, vol. 15, no. 1, pp. 387–401, 2013.

[10] P. Hui, A. Chaintreau, J. Scott, R. Gass, J. Crowcroft, and C. Diot, Pocket switched networks and human mobility in conference environments, in Proc. of ACM WDTN ’05, 2005.

[11] P. Hui, J. Crowcroft, and E. Yoneki. Bubble rap: Social-based forwarding in delay-tolerant networks, IEEE Transactions on Mobile Computing, vol. 10, no. 11, pp. 1576–1589, 2011.

[12] A. Vahdat and D. Becker, Epidemic routing for partially connected ad hoc networks, Technical Report CS-200006, Duke University, 2000.

[13] T. Spyropoulos, K. Psounis, and C. S. Raghavendra, Spray and wait: An efficient routing scheme for intermittently connected mobile networks, in Proceedings of the 2005 ACM SIGCOMM Workshop on Delay-Tolerant Networking, 2005, pp. 252–259.

[14] A. Lindgren, A. Doria, and O. Schelén, Probabilistic routing in intermittently connected networks, ACM SIGMOBILE Mobile Computing and Communications Review, vol. 7, no. 3, pp. 19–20, 2003.

[15] H. Dubois-Ferriere, M. Grossglauser, and M. Vetterli, Age matters: Efficient route discovery in mobile ad hoc networks using encounter ages, in Proceedings of the 4th ACM International Symposium on Mobile Ad Hoc Networking & Computing (MobiHoc 2003), 2003, pp. 257–266.

[16] V. Erramilli, A. Chaintreau, M. Crovella, and C. Diot, Diversity of forwarding paths in pocket switched networks, in Proceedings of the 7th ACM SIGCOMM Conference on Internet Measurement, 2007, pp. 161–174.

[17] V. Erramilli, M. Crovella, A. Chaintreau, and C. Diot, Delegation forwarding, in Proceedings of the 9th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc 2008), 2008, pp. 251–260.

[18] E. M. Daly and M. Haahr, Social network analysis for routing in disconnected delay-tolerant MANETs, in Proceedings of the 8th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc 2007), 2007, pp. 32–40.

[19] P. Hui and J. Crowcroft, How small labels create big improvements, in Pervasive Computing and Communications Workshops, 2007. PerCom Workshops’ 07. Fifth Annual IEEE International Conference on, 2007, pp. 65–70.

[20] F. Li, L. Zhao, C. Zhang, Z. Gao, and Y. Wang, Routing with multi-level cross-community social groups in mobile opportunistic networks, Personal and Ubiquitous Computing, vol. 18, no. 2, pp. 385–396, 2014.

[21] C. Tian, F. Li, L. Jiang, Z. Wang, and Y. Wang, Energy efficient social-based routing for delay tolerant networks, in Prof. of 9th International Conference on Wireless Algorithms, Systems and Applications (WASA 2014), 2014.

[22] W. Gao, Q. Li, B. Zhao, and G. Cao, Social-aware multicast in disruption-tolerant networks, IEEE/ACM Transactions on Networking (TON), vol. 20, no. 5, pp. 1553–1566, 2012.

[23] E. Bulut and B. K. Szymanski, Friendship based routing in delay tolerant mobile social networks, in Proc. of Global Telecommunications Conference (GLOBECOM 2010), 2010, pp. 1–5.

[24] F. Li, H. Jiang, Y. Wang, X. Li, M. Wang, and T. Abdeldjalil, SEBAR: Social energy based routing scheme for mobile social delay tolerant networks, in Proceedings of the 2013 IEEE International Performance Computing and Communications Conference (IPCCC 2013), 2013.

[25] Y. Zhu, C. Zhang, and Y. Wang, Social based throwbox placement in large-scale throwbox-assisted delay tolerant networks, in Proc. of 2014 IEEE International Conference on Communications (ICC 2014), 2014.

[26] Y. Zhu, C. Zhang, F. Li, and Y. Wang, Geo-Social: Routing with location and social metrics in mobile opportunistic networks, in Proc. of 2015 IEEE International Conference on Communications (ICC 2015), 2015.

[27] T. Hossmann, T. Spyropoulos, and F. Legendre, Know thy neighbor: Towards optimal mapping of contacts to social graphs for DTN routing, in Proc. of IEEE INFOCOM 2010, 2010, pp. 1–9.

[28] J. Scott, R. Gass, J. Crowcroft, P. Hui, C. Diot, and A. Chaintreau, Crawdad trace cambridge/haggle/imote/infocom2006 (v. 2009-05-29), http://crawdad.cs.dartmouth.edu/cambridge/haggle/imote/infocom2006, 2009.

Ting Li received the BEng degree from Xidian University in 2012 and is currently a PhD student in the Department of Computer Science at University of North Carolina at Charlotte. Her research interest includes wireless networks, mobile crowd sensing, privacy and security, and mobile social networks.

Chenfei Tian received the BS degree from Chongqing University in 2013 and MEng degree in computer science from the Beijing Institute of Technology in 2016. He is currently a software engineering at Baidu, Inc. His research interest includes delay tolerant networks, wireless networks, and mobile social networks.
Yu Wang is a full professor of computer science at the University of North Carolina at Charlotte. He received the PhD degree in computer science from Illinois Institute of Technology in 2004, the BEng degree and MEng degree in computer science from Tsinghua University, China, in 1998 and 2000, respectively. His research interest includes wireless networks, mobile social networks, sensor networks, mobile crowd sensing, and algorithm design. He has published over 150 refereed papers. He has served as editorial board member of several international journals, including *IEEE Transactions on Parallel and Distributed Systems*. He is a recipient of Ralph E. Powe Junior Faculty Enhancement Awards from Oak Ridge Associated Universities in 2006 and a recipient of Outstanding Faculty Research Award from College of Computing and Informatics at UNC Charlotte in 2008. He won Best Paper Awards from IEEE HICSS-35 (2002), IEEE MASS (2013), IEEE IPCCC (2013) and *Tsinghua Science and Technology* (2015). He is a senior member of the ACM, IEEE, and IEEE Communication Society.

Fan Li received the PhD degree in computer science from the University of North Carolina at Charlotte in 2008, MEng degree in electrical engineering from the University of Delaware in 2004, MEng and BEng degrees in communications and information system from Huazhong University of Science and Technology, China in 2001 and 1998, respectively. She is currently a full professor at School of Computer Science in Beijing Institute of Technology, China. Her current research focuses on wireless networks, ad hoc and sensor networks, and mobile computing. Her papers won Best Paper Awards from IEEE MASS (2013), IEEE IPCCC (2013), ACM MobiHoc (2014), and *Tsinghua Science and Technology* (2015). She is a member of ACM and IEEE.