SEBAR: Social Energy BAsed Routing Scheme for Mobile Social Delay Tolerant Networks

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***Abstract*—Delay Tolerant Networks (DTNs) are intermittently connected networks, such as mobile social networks formed by human-carried mobile devices. Routing in such mobile social DTNs is very challenging as it must handle network partitioning, long delays, and dynamic topology. Recently, social-based approaches, which attempt to exploit social behaviors of DTN nodes to make better routing decision, have drawn tremendous interests in DTN routing design. In this paper, we propose a novel social-based routing approach for mobile social DTNs, where a new metric *social energy* is introduced to quantify the ability of a node to forward packets to others, inspired by general laws in particle physics. Social energy is generated via node encounters and shared by the communities of encountering nodes. Similar to the radiation of energy in physics, the social energy of any node decays over time. Our proposed *Social Energy BAsed Routing* (SEBAR) protocol considers social energy of encountering nodes and is in favor of the node with a higher social energy in its or the destination's social community. Our simulations with real-life wireless traces demonstrate the efficiency and effectiveness of SEBAR method by comparing it with several existing DTN routing schemes.**

I. Introduction

Delay Tolerant Network (DTN) is one of the emerging communication paradigms in the next generation mobile communications. In DTNs, communication is challenged by sporadic and intermittent contacts as well as frequent network partitioning. Thus, the assumption of the existence of an end-to-end path between any source and destination is vanished. This is especially true for mobile social DTNs (also called as *pocket switched networks* [1], [2]), where human-carried mobile devices are moving around in a restricted physical space and occasional contact opportunities among these devices are used to deliver data. Due to the lack of instantaneous end-to-end paths, large transmission delays, and time-varying network topology, classical ad hoc routing protocols perform poorly in these DTNs.

Many opportunity-based routing protocols [2]–[8] have been proposed for DTNs to handle the intermittent connectivity. Most of them adopt "store and forward", where the current node stores and carries the data if there is no connection available, and then makes a forwarding decision when it encounters another node later. Forwarding decision during an encounter usually relies on comparisons between per-node metrics. For example, *FRESH* [7] forwards the packet to the encountering node if it has met the destination more recently than the current node has; while *Greedy-Total* [8] forwards if it meets a node with a higher contact frequency to all other nodes. These simple metrics can be easily obtained from contact history and used to estimate the delivery probability or expected delay to the destination node, however, such estimations are not always accurate. Since mobile devices in mobile social DTNs are used and carried by people, whose behaviors are better described by their social characteristics, new *social-based* approaches [2], [6], [9]–[13] are designed to assist in making forwarding decisions based on social network metrics. For example, *SimBet* [6] prefers a node with a higher social centrality and more common neighbors with the destination as its relay; *Label* [9] and *Group* [11], [12] try to forward message to a node within the same social group of the destination; while *Bubble Rap* [2] forwards data via a hierarchical community structure and chooses the node with higher centrality in the global community or a local community of the destination. These social-based methods take advantages of understanding of social relationships among nodes to make smarter forwarding decisions.

In this paper, we propose a new social-based routing scheme for mobile social DTNs: *Social Energy BAsed Routing* (SEBAR). Inspired by general laws in particle physics, we introduce a novel social metric *social energy* to quantify the social ability of a node to forward messages to others. Social energy is generated via node encounters and shared by the communities of encountering nodes. An active node with many encounters will have a higher social energy, and a community with many encounters among its members or with members from other communities will have a higher social energy too. In addition, similar to the radiation of energy in physics, the social energy of any node decays over time unless it gains from new encounters. Our proposed SEBAR protocol considers social energy of encountering nodes and is greedily in favor of the node with higher social energy in its or the destination's social community. We conduct extensive simulations using real-life tracing data [14], [15] to compare the proposed method with several existing methods. Our

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simulation results demonstrate the efficiency and effectiveness of SEBAR scheme.

The rest of the paper is organized as follows. Section II briefly reviews existing DTN routing protocols. Section III provides our detailed design of SEBAR scheme for mobile social delay tolerant networks. Section IV presents our simulation results over two real-life mobile tracing data sets. Finally, Section V concludes the paper.

II. Related Work

In the previous studies, many routing algorithms have been introduced for DTNs based on different techniques (roughly in three types: message-ferry-based, opportunity-based and prediction-based). Here, we mainly focus on *opportunity-based routing* where packets are forwarded using available communication opportunities when nodes encounter with each other. By taking advantages of mobility of intermediate nodes, it is expected to deliver messages eventually, but without guarantees.

The simplest routing method is *epidemic routing* [3], in which copies of packets are forwarded to any encountering nodes. This flooding-based method can guarantee the best delivery ratio, but with possible huge message overheads. To reduce the overheads, many routing methods restrict the number of message replicas in the network to a certain constant (such as in *Spray and Wait* [4]) or just one (such as in *SimBet* [6]) or a small one by only replicating the message when certain condition is met (such as in *delegation forwarding* [5]). We call the method which allows multiple replicas and the method which allows a single replica as multi-copy routing and single-copy routing, respectively. In single-copy routing, the current node will not hold the copy of the packet after forwarding it to the selected encountering node. Forwarding decision usually relies on certain type of quality metric and the packet is only forwarded to the encountering node with higher quality metric. Examples include *FRESH* [7] (picking the node which has met the destination more recently), *Greedy-Total* [8] (picking the node with a higher encounter frequency to all other nodes), or *MobySpace* [16] (picking the node which has more location similarity with the destination).

Lately, the consideration of social characteristics provides a new perspective in the design of routing protocols for DTNs [13], especially where mobile devices are carried by people (such as pocket switched networks). Social-based DTN routing uses the knowledge of social characteristics and relationships among mobile users for making better forwarding decisions. For example, nodes with higher social centrality (more popular) are selected as relay nodes (such as in *SimBet* [6], *Bubble Rap* [2], and *Friendship*-based routing [10]); or nodes within the same community (or social group) with the destination are preferred as relay nodes (such as in *Label* routing [9], *Bubble Rap* [2], *Friendship*-based routing [10], and *Group*-based routing [11], [12]). Note that these social characteristics and relationships among mobile users are usually long-term characteristics and less volatile than node mobility. Our proposed SEBAR method belongs to this category and uses the novel concept of social energy to quantify the social ability of a node to forward messages to others. The calculation of social energy considers both node's centrality and community structure. However, it is completely different from the traditional community-based methods (such as *Bubble Rap* [2]).

III. Social Energy BAsed Routing (SEBAR)

In this section, we provide the detailed design of the proposed Social Energy BAsed Routing (SEBAR) scheme. We will discuss the community detection method we used, and then introduce the key concept of SEBAR: a new social metric named social energy and explain how it can be calculated and decayed over time. Last, we present our social energy based forwarding scheme used in SEBAR.

A. Community Detection

Community is an important concept in sociology which is usually defined as a group of interacting people living in a common location and can naturally reflect social relationships among people. It has been shown that a member of a given community is more likely to interact with another member of the same community than with a randomly chosen member of the population. This is also true in mobile social DTNs, i.e., there exists communities among mobile devices in which nodes are highly connected to each other than nodes outside the community [2], [9]. Therefore, it is crucial to detect and understand the communities in mobile social DTNs. Our proposed social metric, social energy, is calculated based on the community structure and shared by members of the community too. The proposed SEBAR forwarding scheme also uses the community information to make the forwarding decision.

Many proposed community detection algorithms are available for identifying social communities in social networks, such as k-clique [17] and weighted network analysis (WNA) [18]. WNA can detect communities over a weighted network but can not support overlapping communities, while traditional k-clique method can detect overlapping communities over a binary network. Since in real social life, one person can belong to multiple social communities. Our SEBAR chooses k-clique method to detect overlapping communities in mobile real traces. There are two key parameters in k-clique method: ω and k. To convert the original contact graph (the weighted one with the total contact duration as the edge weight) into a binary social graph, we use a predefined threshold ω to decide whether there is an edge between two nodes. If the edge weight between two nodes is equal to or larger than ω, we add one edge between them in social graph to represent strong social tie between these two nodes. Larger threshold ω represents higher requirement on social strength and results in sparse but more cohesive network. k describes the size of complete subgraph which contains k nodes fully connected to each other. If two k-cliques share $k-1$ nodes, these two k-cliques are adjacent and can be added to a k-clique community.

As k increases, the communities shrink, but become more tight since their members have to be part of at least one k-clique. Notice that some nodes which do not have enough connections with others may become isolated, thus k-clique method may result in an incomplete coverage. After applying the k-clique method, multiple overlapping communities can be detected. A single node may belong to multiple communities. Hereafter, C_j represents the j-th community in the network, $v_i \in C_j$ means that node v_i belongs to C_j and $C(v_i)$ represents all communities of v_i.

B. Social Energy

We now introduce the concept of *social energy* which is inspired from nature of particles. In particle physics, energy could be generated when two particles collide. Similarly, when two mobile nodes v_k and v_l encounter each other, a collision happens between them and this collision generates certain amount of social energy, i.e., $N_{k,l}$. This generated energy will be evenly distributed to these two nodes. Each node contributes partial of this generated energy (i.e., $p \cdot \frac{N_{k,l}}{2}$) to its community (if v_k belongs to n_k communities, then this energy is shared by all of them, i.e., $p \cdot \frac{N_{k,l}}{2n_k}$ for each) and holds the remaining part of energy $(1-p) \cdot \frac{N_{k,l}}{2}$. Here, p (called as energy percentage hereafter) indicates the ratio of energy contributed by a node to the communities it belongs to. The community gains energy from all its member nodes and distributes the community energy to its members based on the node's *community centrality*, which can be defined as follows:

$$c_k(j) = \frac{\sum_{i=1}^{m_k} D_k(i)}{\sum_{any\ v_x \in C_j} \sum_{i=1}^{m_x} D_x(i)}. \tag{1}$$

Here $c_k(j)$ is the community centrality of node v_k in community C_j and $D_k(i)$ is the duration of i-th contact of v_k with other nodes. We assume that m_k is the total number of encounters of v_k. $\sum_{i=1}^{m_k} D_k(i)$ is the total contact duration of v_k, while $\sum_{any\ v_x \in C_j} \sum_{i=1}^{m_x} D_x(i)$ is the summation of total contact duration of all member nodes in community C_j. Overall, the community centrality is defined as the ratio between these two duration values and must be a value between 0 and 1. A more active node will have a larger community centrality, thus can gain more energy from the community than others.

The social energy of each node aims to quantify the social ability of forwarding packets to other nodes, which consists of two parts: the reserved energy generated by itself from direct node collisions with other nodes and the reallocated energy gained from its communities, as shown in the following equation.

$$\begin{aligned} \mathbb{E}_k &= \mathbb{E}\_\mathbb{N}_k + \mathbb{E}\_\mathbb{C}_k \\ &= \sum_{i=1}^{m_k} \mathbb{E}\_\mathbb{N}_k(i) + \sum_{any\ C_j \ni v_k} \mathbb{E}\_\mathbb{C}_k(j). \end{aligned} \tag{2}$$

TABLE I
NOTATIONS USED

Term	Definition
$C(v_k)$	communities that v_k belongs to
p	energy percentage contributed to the community
$N_{k,l}$ ($N_{k,l}(i)$)	energy generated by (i-th) encounter between v_k and v_l
$c_k(j)$	community centrality of node v_k in community C_j
n_k	total no. of communities that v_k belongs to
m_k (m_k^t)	total no. of encounters that v_k has (during time $[t-\tau, t]$)
$D_k(i)$	contact duration of i-th encounter of node v_k
$\mathbb{E}_k$ ($\mathbb{E}_k^t$)	social energy of node v_k (at time t)
$\mathbb{E}\_\mathbb{N}_k$ ($\mathbb{E}\_\mathbb{N}_k^t$)	energy of v_k gained from direct encounters (at time t)
$\mathbb{E}\_\mathbb{C}_k$ ($\mathbb{E}\_\mathbb{C}_k^t$)	energy of v_k allocated from multiple communities which node v_k belongs to (at time t)
$\mathbb{E}\_\mathbb{N}_k(i)$	energy gained from ith encounter of node v_k
$\mathbb{E}\_\mathbb{C}_k(j)$	energy gained from community C_j that v_k belongs to
ξ	energy decay coefficient
τ	decay period

Here $\mathbb{E}_k$ is the social energy of node v_k; $\mathbb{E}\_\mathbb{N}_k$ is the energy of node v_k gained from its own encounters; $\mathbb{E}\_\mathbb{C}_k$ is the energy allocated from n_k communities which node v_k belongs to. $\mathbb{E}\_\mathbb{N}_k(i)$ measures the energy gained from ith encounter of node v_k and can be calculated as:

$$\mathbb{E}\_\mathbb{N}_k(i) = (1-p) \cdot \frac{N_{k,l}(i)}{2}. \tag{3}$$

Thus, $\sum_{i=1}^{m_k} \mathbb{E}\_\mathbb{N}_k(i)$ is the total social energy of v_k gained from its encountering with other nodes (m_k times). $\mathbb{E}\_\mathbb{C}_k(j)$ describes the energy of v_k gained from the community C_j that v_k belongs to, and can be calculated as follows.

$$\mathbb{E}\_\mathbb{C}_k(j) = c_k(j) \cdot \sum_{any\ v_x \in C_j} \sum_{i=1}^{m_x} p \cdot \frac{N_{x,l}(i)}{2n_k}. \tag{4}$$

Recall that $c_k(j)$ is node v_k's community centrality, which decides how much percent of community energy is distributed to v_k. $\sum_{any\ v_x \in C_j} \sum_{i=1}^{m_x} p \cdot \frac{N_{x,l}(i)}{2n_k}$ formulates the social energy of community C_j that v_k belongs to. $\sum_{any\ C_j \ni v_k} \mathbb{E}\_\mathbb{C}_k(j)$ shows the total social energy gained from all communities that node v_k belongs to. Table I lists all notations used in this paper.

Figure 1 illustrates an example of social energy generated by a node collision and how this energy is distributed and shared with the community and other members. Note that each node (person) plays diverse roles in different communities, so it has different social energy levels in its communities. Overall, when a node encounters with others more frequently, there will be more energy generated from node collisions and this node will also have higher social energy. Nodes with higher social energy are more active in both its own community and the whole network, thus they may have larger probability to deliver the packet to the destination. Similarly, when a node belongs to more communities, it can obtain more energy allocated from multiple communities, which obviously makes it more popular (higher social energy) and more suitable for serving as the relay node. Therefore, in our proposed SEBAR scheme, social energy is used as the routing metric to decide

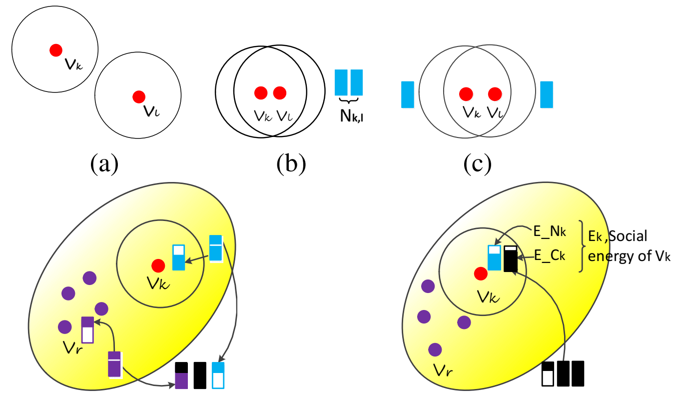


Fig. 1. **An illustration of the social energy of node v_k:** (a) two nodes v_k and v_l. The circle centered at the node is its transmission range; (b) v_k encounters with v_l, and this collision generates $N_{k,l}$ units of energy; (c) $N_{k,l}$ units of energy is split evenly by v_k and v_l; (d) v_k contributes p percentage of energy generated by encounters to its community and reserves remaining $(1-p)$ percentage to itself. v_k's community gets energy from all its member nodes, such as v_k and v_r. The yellow eclipse indicates the community that v_k and v_r belong to; (e) the community reallocates its energy to its members based on their community centralities c_k. $\mathbb{E}\_\mathbb{N}_k$ (blue block) is the energy gained by direct node encounters of v_k, $\mathbb{E}\_\mathbb{C}_k$ (black block) is the energy reallocated by node v_k's communities. Social energy $\mathbb{E}_k$ is the summation of these energy.

which encountering node to be selected as the relay node. Finally, there exists isolated node that does not belong to any community, thus its community energy is zero and it can become active only by encountering with other nodes.

C. Energy Decay

Notice that the social energy of each node will always increase by its definition, since any node collision (encounter among nodes) will increase the social energy. This may not be reasonable in reality as encounters occurred long time ago may not reflect the current social ability of forwarding of a node. Like in thermotics, all objects radiate thermal energy which results in a drop in temperature on the macroscopic scale. Inspired by this phenomenon, we introduce a simple energy decay mechanism to describe the aging of node forwarding capability and community active level. We define an energy decay coefficient, denoted by ξ, $(0 \le \xi \le 1)$, so that for every τ seconds, the social energy of a node (or a community) loses about ξ portion. The intuition is that the social energy of node decreases over time, so the node needs to be active to remain its energy level to be selected as the relay node, otherwise, its energy can decay to be zero. Here both ξ and τ are adjustable parameters.

Therefore, we modify social energy of node v_k (i.e., Equation 2) as:

$$\mathbb{E}_k^t = \mathbb{E}\_\mathbb{N}_k^t + \mathbb{E}\_\mathbb{C}_k^t. \tag{5}$$

where $\mathbb{E}_k^t$, $\mathbb{E}\_\mathbb{N}_k^t$, and $\mathbb{E}\_\mathbb{C}_k^t$ are denoted as social energy, energy gained by direct encounters, and energy allocated by communities of node v_k at time t respectively.

For $\mathbb{E}\_\mathbb{N}_k^t$, it can be calculated as follows:

$$\mathbb{E}\_\mathbb{N}_k^t = (1-\xi)\mathbb{E}\_\mathbb{N}_k^{t-\tau} + \sum_{i=1}^{m_k^t} \mathbb{E}\_\mathbb{N}_k(i). \tag{6}$$

The first part of the right side of this equation is the remained energy gained by direct encounters at the time $t-\tau$ after decay, and the second part is the newly gained energy due to direct encounters during the period of $[t-\tau, t]$. Here, we assume there are m_k^t encounters happened for v_k in that period.

Similarly, $\mathbb{E}\_\mathbb{C}_k^t$ can be calculated as follows:

$$\mathbb{E}\_\mathbb{C}_k^t = (1-\xi)\mathbb{E}\_\mathbb{C}_k^{t-\tau} + \sum_{\text{any } C_j \ni v_k} (c_k(j) \cdot \sum_{\text{any } v_x \in C_j} \sum_{i=1}^{m_x^t} p \cdot \frac{N_{x,l}(i)}{2n_k}). \tag{7}$$

Here, m_x^t is the number of encounters of node v_x in the period of $[t-\tau, t]$.

The decay stops when node energy or community energy attenuates to zero. One node can return to its active status if it encounters new nodes or its communities have new encountering events. The decay mechanism can reflect time-varying characteristic of node forwarding capability and avoid obsolete historical information to interfere node current status.

D. SEBAR Forwarding Scheme

Based on the newly defined social energy and energy decay mechanism, we now describe our Social Energy BAsed Routing (SEBAR) scheme. Forwarding is carried out as follows. Assume that a node v_k carries q copies[1] of a packet to destination v_d and encounters another node v_l. If v_l already has a copy of this packet, v_k will continue holding the packet. If v_l is the destination (i.e., $v_l = v_d$), v_k will forward the packet to v_l. Otherwise, SEBAR will try to forward half of the copies to a relay node who has higher social energy. There are two cases where the forwarding happens: (1) v_k does not belong to v_d's community and $\mathbb{E}_k < \mathbb{E}_l$; and (2) both v_k and v_l belong to v_d's community and $\mathbb{E}\_\mathbb{C}_k < \mathbb{E}\_\mathbb{C}_l$. Otherwise, v_k will continue holding the packet. In other words, when the packet does not reach the destination's community, SEBAR looks for more active relay nodes (with higher overall social energy) which may allow fast transfer towards the destination or its community. When the packet has reached the destination's community, SEBAR looks for more active relay nodes within the community (nodes with higher social energy gained from the community). Recall that such portion of social energy is distributed based on community centrality. Algorithm 1 shows the detailed forwarding algorithm.

IV. Simulation Results

We have conducted extensive experiments over real-life wireless traces to evaluate our proposed SEBAR approach and compared it with the following existing DTN routing methods.

[1]Here, we assume a multi-copy routing scheme where the number of copies is restricted (similar to [4]). However, our proposed scheme can also work with single copy routing.

Algorithm 1 Social Energy BAsed Routing (SEBAR)

When node v_k with q copies of packet M destined to v_d meets a node v_l.

Calculate social energy of v_k and v_l: $\mathbb{E}_k$ and $\mathbb{E}_l$ (including $\mathbb{E}\_\mathbb{C}_k$ and $\mathbb{E}\_\mathbb{C}_l$)
if v_l carries a copy of M **then**
    v_k holds on copies of M
else if $v_l = v_d$ **then**
    v_k forwards a copy of M to v_l
else if $v_k \notin C(v_d)$ and $\mathbb{E}_k < \mathbb{E}_l$ **then**
    v_k forwards $\lfloor q/2 \rfloor$ copies of M to v_l
else if $v_k, v_l \in C(v_d)$ and $\mathbb{E}\_\mathbb{C}_k < \mathbb{E}\_\mathbb{C}_l$ **then**
    v_k forwards $\lfloor q/2 \rfloor$ copies of M to v_l
else
    v_k holds on copies of M

- **Epidemic [3]:** during any encounter, the message is forwarded to all encountered nodes. It shows the upper bound of delivery ratio of any routing method.
- **Spray and Wait [4]:** it is composed of two phases. In the spray phase, when node v_i carrying $k > 1$ copies meets node v_j, it will forward half of the total number of copies to node v_j. When any node eventually gives away all of its copies, except for one, it automatically turns into the wait phase where it waits for a direct transmission with the destination node.
- **Greedy-Total [8]:** the message is only forwarded from v_i to v_j if v_j has more total contacts with all other nodes than v_i does.
- **Bubble Rap [2]:** it consists of two phases: the bubble-rap phase based on global centrality and the bubble-rap phase based on local centrality. When a node v_i has a message for destination v_d, it first bubbles up the message to the node with greater global centrality until the message reaches one node which is in the same community with the destination, then the message is forwarded to a more popular node based on local centrality.

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

- **Delivery ratio:** the average percentage of successfully delivered messages from the sources to the destinations.
- **Average hops:** the average number of hops during each successful delivery from the sources to the destinations.
- **Number of Forwarding:** the average number of message forwardings in the network during the whole period.
- **Delay:** the average time duration of successfully delivered messages from the sources to the destinations.

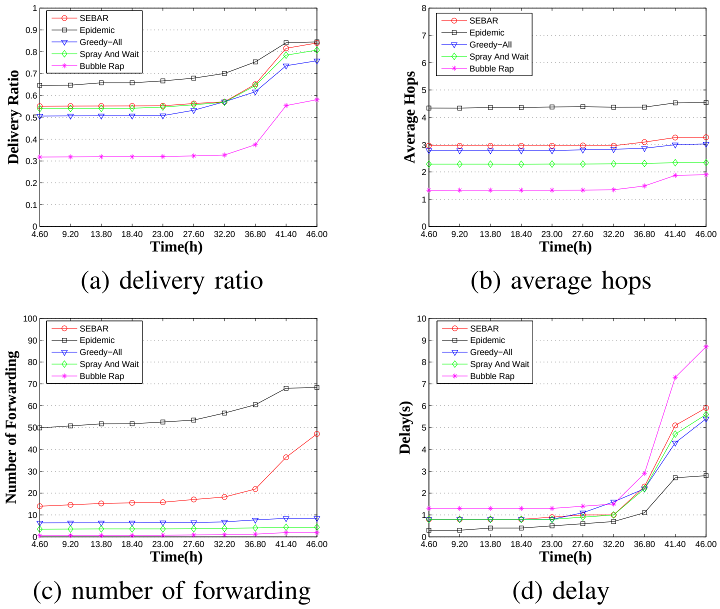
A. Results on InfoCom 2006 Bluetooth Trace Data

In order to test our proposed SEBAR method in a realistic mobile social DTN, we first use the InfoCom 2006 trace data [14]. This trace data includes connections among 78 mobile iMote Bluetooth nodes carried by participants of a student workshop, 20 stationary nodes deployed throughout the area for four days during InfoCom 2006 in Barcelona, Spain. Each record in the data set contains information about the IDs of the device who recorded the sightings and the device who was seen. It also includes the start time and end time for certain contact, so the duration time of contacts between two nodes can be calculated. In all simulations, we only consider the 78 mobile nodes carried by students because we focus on studying the performance of SEBAR in mobile social DTN scenario. The contact information from the first 46 hours is treated as historical statistics to obtain original contact duration graph (social network) for community detection, then we evaluate the performance of routing tasks over the remaining 46 hours. Each participant tries to send a message to all other nodes, i.e., there are $78 \times 77/2 = 3003$ routing tasks performed. The number of message replicas allowed is limited to 5 except for epidemic routing (where no limitation is placed). We choose k-clique method [17] to discover communities since it allows that one node belongs to more than one community. To convert the contact duration weighted graph into a binary graph, we only keep the edges with stronger ties than a threshold weight ω. In our simulation, we set ω to 4500s, i.e., we add an edge between two nodes if their total contact duration is larger than 4500s. The settings of our simulations and results from k-clique method are listed in Table II.

TABLE II
PARAMETERS USED IN SIMULATIONS OVER INFOCOM 2006 TRACE DATA

Parameter	Value or Range
time window	$165,600$s or 46 hours
number of mobile nodes	78
k value for k-clique	4
threshold ω of k-clique	4500s
number of isolated nodes	4
number of nodes belonging to > 1 communities	8
number of communities	3
size of each community	73, 5, 4
number of routing tasks	$\binom{78}{2} = 3003$
number of replicas allowed	5

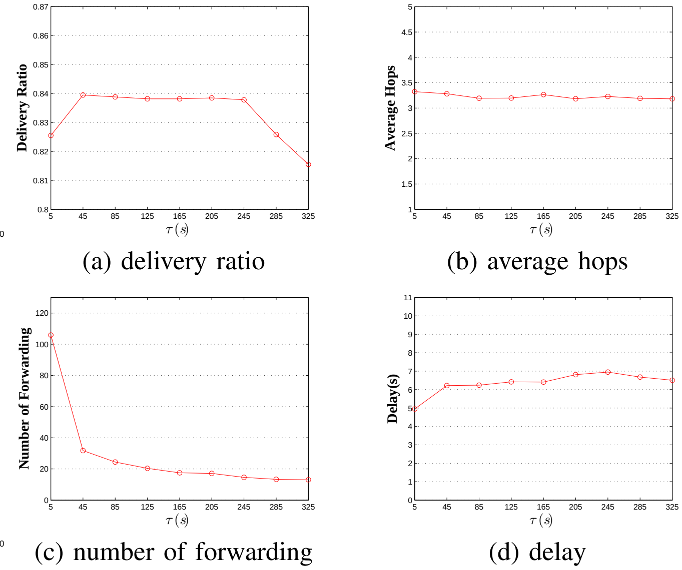
In the first set of simulations, we compare our proposed routing algorithm with other four routing methods. We use multi-copy versions in which the total number of copies is limited by 5, except for epidemic routing. Besides, we set community energy percentage p to 0.25 and decay time τ to 20 seconds. In this group of simulations, we use default Bubble Rap parameters as recommended in [2]. As Figure 2 shows, our SEBAR algorithm achieves better delivery ratio than any others except for epidemic routing. However, even though epidemic routing achieves best in terms of delivery ratio, it costs huge number of forwardings and hops as shown in Figure 2(b) and Figure 2(c) respectively. Compared with other DTN methods, SEBAR has relevantly higher number of forwarding, but this is a cost with higher delivery ratio. In terms of average hop number and delay, SEBAR method is at the similar level with those of other existing methods. This observation confirms the efficiency of introducing social energy in the design of energy based routing.



(a) delivery ratio (b) average hops

(c) number of forwarding (d) delay

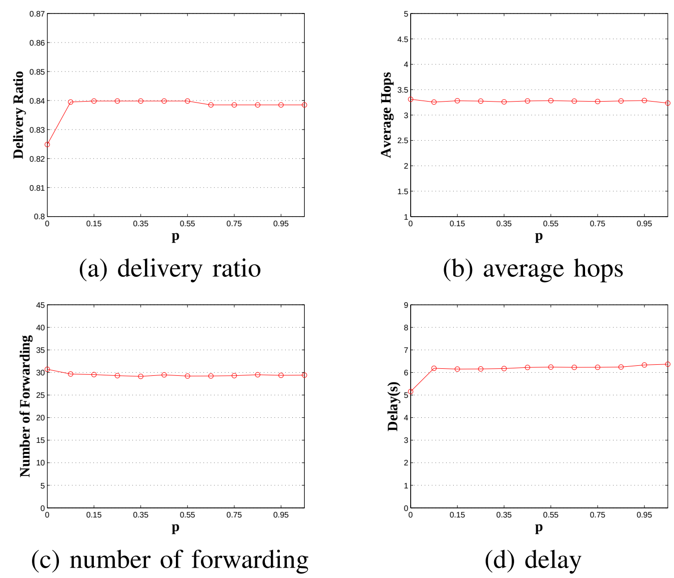
Fig. 2. Simulation results of all different routing algorithms (over InfoCom 2006 data set) with $p = 0.25$ and $\tau = 20$ seconds.



(a) delivery ratio (b) average hops

(c) number of forwarding (d) delay

Fig. 3. Simulation results of SEBAR (over InfoCom 2006 data set) with fixed p ($p = 0.5$) and varying τ.



(a) delivery ratio (b) average hops

(c) number of forwarding (d) delay

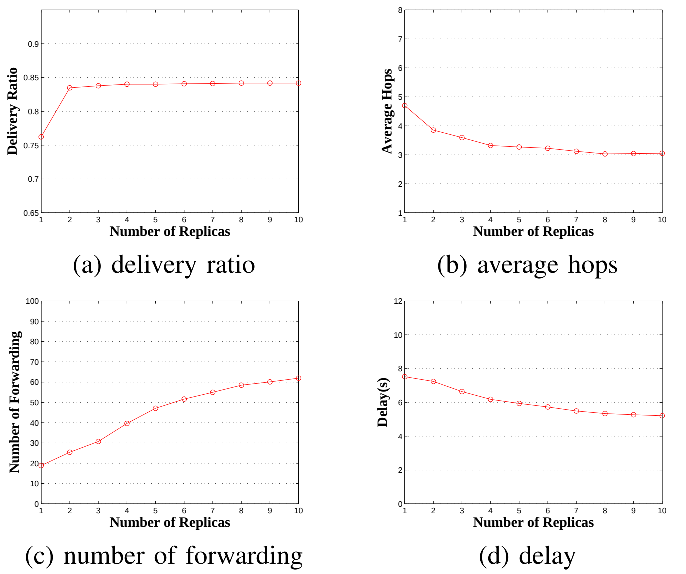
Fig. 4. Simulation results of SEBAR (over InfoCom 2006 data set) with varying p and fixed τ ($\tau = 20$ seconds).

In the second set of simulations, we evaluate how SEBAR performs with the variation of two key parameters: community energy percentage p and decay period τ. We first set p to 0.5 and test SEBAR algorithm with varying decay period τ. Figure 3 shows results. As shown in Figure 3(a), the delivery ratio goes up, stays at the certain level, and then descends with the increase of τ. That means decaying too fast or too slow cannot accurately describe the changes in node's forwarding capability. Figure 3(c) also shows that when the decay period is small (thus very fast decay), there could be huge amount of forwards in the network. Regarding the average hops and delay, they change little with the varying of τ (as shown in Figure 3(b) and (d)). We then specify τ at 20 seconds and test SEBAR method with different community energy percentage p. Note that when $p = 0$, the energy generated by node encounters will only share between encountering nodes without contribution to the communities. When $p = 1$, the energy generated by node encounters will be all contributed to their communities. From Figure 4(a), when p is within the range from 0.15 to 0.55, SEBAR has higher delivery ratio than that of when $p = 0$ and $p = 1$, which confirms that contributing portion of energy gained from encounters to the community does benefit packet delivery. The variation of p does not affect other routing metrics much as shown in Figure 4.

In the third set of simulations, we test SEBAR with different number of replicas (from 1 to 10). Community activity percentage p is set to be 0.25 and decay period τ is specified at 20 seconds. From Figure 5, we can observe that more number of replicas results in higher delivery ratio, smaller average hops and delay. It is obviously that the number of forwards gets larger with the addition number of replicas.

B. Results on MIT Reality Mining Cellular Trace Data

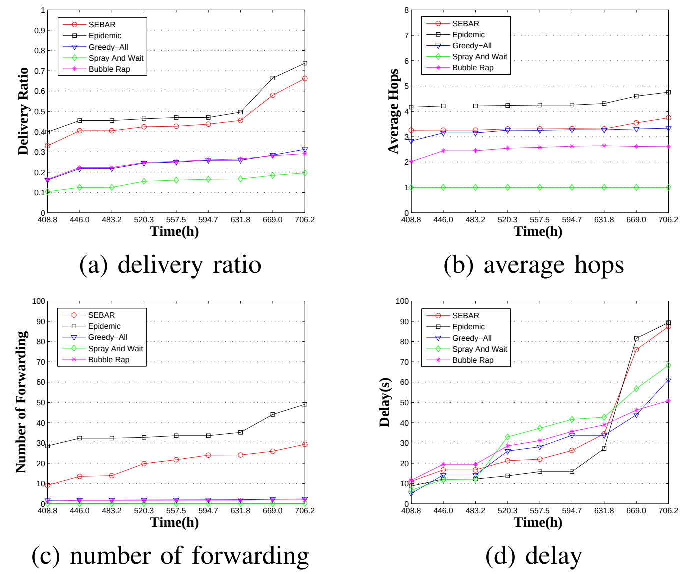
Since the InfoCom 2006 data set only lasts for four days, we want to evaluate our SEBAR method over a large mobile data set. MIT reality mining project [15] was conducted during the months from September, 2004 to June, 2005 at the MIT Media Laboratory. One hundred Nokia 6600 smart phones were pre-installed with several pieces of software that recorded mobile phone data about call logs, cell tower IDs, application usage, phone status and Bluetooth devices in proximity of 5 to 10 meters. Most of the smart phone users are either students or faculties from MIT. We extract trace data for about one month session (i.e., March, 2005) from MIT data set and choose 65



(a) delivery ratio (b) average hops

(c) number of forwarding (d) delay

Fig. 5. Simulation results of SEBAR (over InfoCom 2006 data set) with increasing number of replicas.



(a) delivery ratio (b) average hops

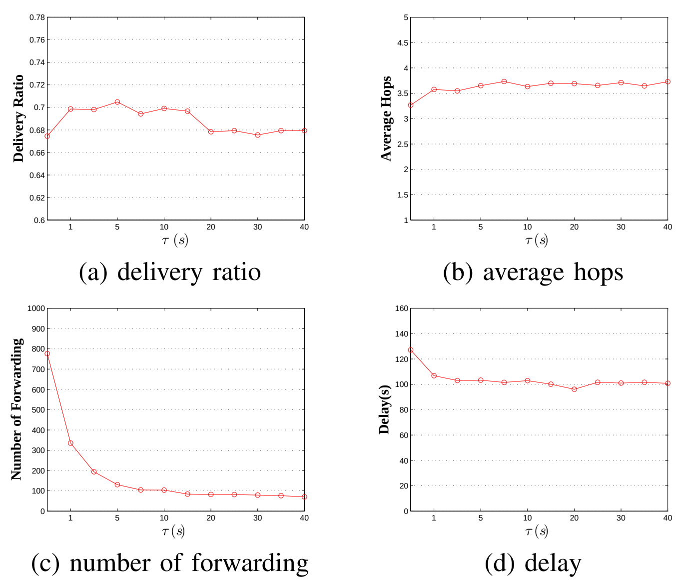
(c) number of forwarding (d) delay

Fig. 6. Simulation results of all different routing algorithms (over MIT Reality data set) with $p = 0.9$ and $\tau = 50$ seconds.

TABLE III

PARAMETERS USED IN SIMULATIONS OVER MIT REALITY TRACE DATA

Parameter	Value or Range
time window	March, 2005
number of mobile nodes	65
k value for k-clique	3
threshold ω of k-clique	6900s
number of isolated nodes	15
number of nodes belonging to > 1 communities	5
number of communities	5
size of each community	27, 15, 3, 7, 3
number of routing tasks	$\binom{65}{2} = 2080$
number of replicas allowed	5



(a) delivery ratio (b) average hops

(c) number of forwarding (d) delay

Fig. 7. Simulation results of SEBAR (over MIT Reality data set) with fixed p ($p = 0.5$) and varying τ.

relatively active users as the sources and destinations. The contact information from the first half month is treated as historical statistics to obtain original contact duration graph and detect community. Evaluations are performed over the remaining half month for $65 \times 64/2 = 2080$ routing tasks. The number of message replicas allowed is limited to 5 except for epidemic routing. Table III summaries the parameters used for MIT data set.

Similar to the simulations over InfoCom 2006 data set, three sets of simulations are performed. Figure 6 to Figure 9 show all the results. Overall the conclusions are consistent with previous experiments. (1) The delivery ratio of our proposed SEBAR algorithm is much better than those of other methods, and even close to that of epidemic routing (as shown in Figure 6(a)); in addition, SEBAR has much less number of forwarding and smaller delay and hop number than epidemic routing (as shown in Figure 6(b), (c) and (d)). (2) Decay period τ needs to be carefully picked. Too fast or slow decay may not lead to the optimal performance, as shown in Figure 7. (3) Community energy percentage p may also affect the performances, and the contribution of energy to communities is definitely beneficial to the energy based routing method (as shown in Figure 8). (4) As the number of replicas allowed increases, SEBAR algorithm can achieve higher delivery ratio, lower average hops and shorter delay with the increasing number of forwarding (as shown in Figure 9).

V. CONCLUSION

In this paper, we propose a new social-based routing approach for mobile social DTNs, which uses a novel social energy metric to quantify the ability of a node to forward packets to others. We present detailed methods to calculate the generated energy from node encounters and share this energy with encountering nodes and communities. In addition, we also introduce a simple decay mechanism to handle the aging

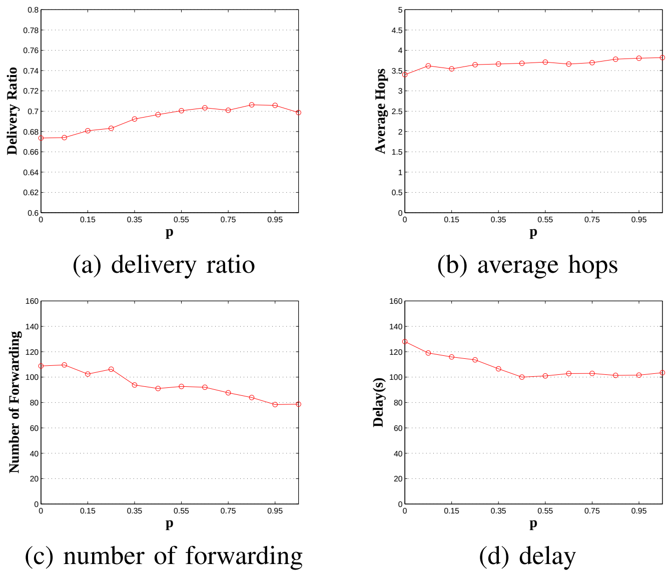


Fig. 8. Simulation results of SEBAR (over MIT Reality data set) with varying p and fixed τ ($\tau = 50$ seconds).

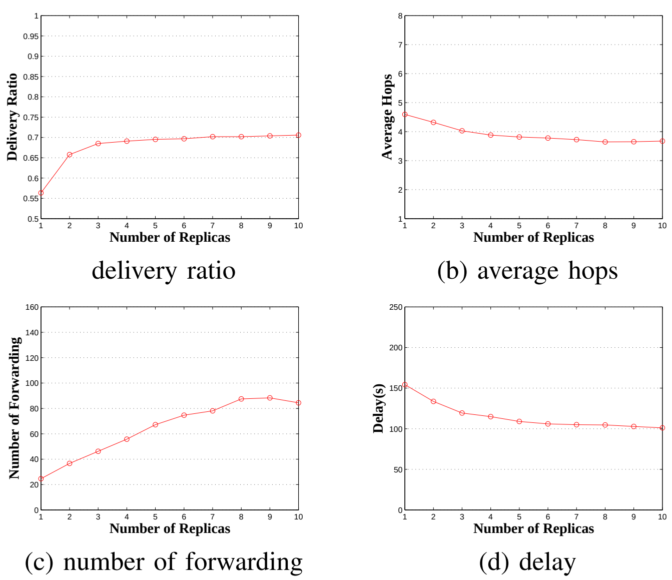


Fig. 9. Simulation results of SEBAR (over MIT Reality data set) with increasing number of replicas.

of encounters. Our proposed Social Energy BAsed Routing protocol considers social energy of encountering nodes and is in favor of the node with higher social energy in its or the destination's social community. Extensive simulations have been conducted with real-life wireless traces. Simulation results confirm the efficiency and effectiveness of SEBAR method.

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