A Social-Based Cyber-Physical System For Distributed Message Transmission

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ABSTRACT

The explosive increase of the availability of personal mobile devices has brought about a significant amount of peer-to-peer communication opportunities upon their encountering, which can be exploited to realize distributed message transmission among mobile devices. However, the opportunistic encountering among mobile devices, which is determined by the mobility of their holders, has introduced great difficulties on efficiently transmitting a message to its designated destination. Actually, people usually present a certain pattern on daily mobility. Further, device holders often belong to a certain social network community. Therefore, in this paper, we propose a social-based cyber-physical system for distributed message transmission, namely SocMessaging, by integrating both the mobility pattern and the social network of device holders. When selecting an encountered node for message relay, in addition to the node's historical encountering records with the destination node, SocMessaging also considers its social closeness with the destination node. Then, the message is always transmitted to the node that is most likely to meet its destination. As a result, SocMessaging closely connects the cyber world (i.e., network), physical world (i.e., people) and social network (i.e., social connection). Finally, our experimental results demonstrate the efficiency of the proposed system in message transmission between device holders.

Keywords: Wireless networks; Social networks, Cyber-physical systems

1. INTRODUCTION

The popularity of personal mobile devices, e.g., smartphones and tablets, has experienced significant increase in recent years. For example, the number of smartphone users had reached 1 billion in 2012 and is expected to surpass 2 billion in 2015.[1] Considering the fact that mobile devices move along with their holders, the encountering between two people also denotes a peer-to-peer communication opportunity for their carried mobile devices. Such communication opportunities do not depend on the infrastructure network and thereby can be utilized for some interesting applications, such as file sharing,[2,3] proximity-based mobile social networking service,[4,5] and distributed message forwarding.[6,7] Among these applications, we are particularly interested in the distributed message transmission among mobile users. In such a system, messages generated by different users can be transmitted to other users inside or outside their social groups even when no infrastructure exists. That is, such a system can potentially connect the cyber world (i.e., network), physical world (i.e., people), and social network (i.e., social connection among people). We use device, node and user interchangeably in this paper.

Due to the indeterministic property of human mobility, the encountering among devices is opportunistic. Therefore, the network consisting of personal mobile devices without infrastructures is also called mobile opportunistic network (MON).[8–10] In such a network, the opportunistic communication opportunity, i.e., encountering, makes the efficient message transmission non-trivial. For example, purely relaying on the generator of a message to meet the destination device to deliver the message is obviously not efficient since the meeting among people is not deterministic. Then, selecting a device with a high probability to meet the destination device of a message as

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the relay device for the message can clearly reduce the delay to deliver the message to its destination. However, how to effectively select such a relay node in a distributed manner is also not easy.

Considering the fact that human mobility usually presents certain patterns, some researchers have proposed to exploit previous encountering records to predict future meeting possibility.[6,8,11–13] Then, each message is always transmitted to the node with a higher probability to meet its destination to gradually reach its destination. However, such a relay node selection method only focuses on the direct encountering probability but may ignore other good relay candidates. For example, a node that rarely meets the destination of a message may often meet nodes that frequently meet the destination. In these methods, such a node can hardly be selected as the relay node, thereby failing to fully utilize forwarding opportunities.

On the other hand, people often belong to certain social networks (i.e., local communities), e.g., students belonging to the same lab and colleagues in the same building. Due to the social connections, people are more likely to meet with people within their social communities. Such a property has also been utilized to realize efficient message transmission in MONs.[3,5,14–16] In these methods, a message is always forwarded to the node that has closer social closeness or similarity with the destination node. These methods can gradually forward a message closer and closer to the destination community, i.e., to places where the destination appears frequently or people the destination often meet. However, they lack a direct indication on how likely a node can meet the destination when the message has reached the destination community.

Therefore, in this paper, we combine both the previous encountering records and the social network to design an efficient social-based cyber-physical system for distributed message transmission, called SocMessaging. In SocMessaging, users generate messages to be transmitted to others through the main interface on their mobile devices. These messages are exchanged among mobile devices during their encountering to gradually reach the destination devices. The whole process is completed distributively without the support from the infrastructure based network. The key of the SocMessaging system is an effective relay node selection algorithm that considers both encountering records and social closeness. It can select nodes that are either more likely to meet the destination or are socially closer with the destinations or both as the relay nodes in order to transmit messages to their destinations. Finally, our trace-based experiments demonstrate the efficiency of SocMessaging in message transmission.

The remainder of this paper is arranged as follows. Section 2 introduces related work. Section 3 presents the detailed design of the SocMessaging system. In Section 4, the performance of SocMessaging is evaluated through trace-driven experiments. Section 5 concludes this paper with remarks on our future work.

2. RELATED WORK

As mentioned in the introduction, the message transmission methods for MONs can generically be classified as two groups: encountering records (or probability) based methods[6,8,11–13] and social network based methods.[3,5,14–16] We introduce the related works in the two groups separately in the following.

2.1 Encounter Record based Methods

In this group of methods, previous encounter records are utilized to deduce future meeting probabilities. In PROPHET,[6] each node updates its future encountering possibility with another node when meeting it. The probability also ages over time. Then, a message is always forwarded to the node with higher probability to meet its destination. HiBop[8] considers the encountering records with the destination's contexts, e.g., residence and hobbies, to forward messages. That is, it forwards the message to nodes with higher context similarity with its destination. In addition to deducing each node's future probabilities to meet others, MaxProp[11] also transmits messages that are more likely to be delivered first. Based on PROPHET and HiBop, RAPID[12] and MaxContribution[13] first deduce each node's future meeting probabilities with others and then further specify different message transmission and storage priorities, i.e., which messages should be transmitted or stored first, to realize different performance objectives such as maximal success rate and minimal delay.

Figure 1: The system structure of SoCMessaging.

2.2 Social Network based Methods

This group of methods try to utilize the social network properties to select the relay node that can realize efficient message transmission. In MOPS,[3] frequently encountered nodes are grouped as communities, and the nodes that often meet nodes in other communities are selected as the ambassadors for inter-community communication. Then, it builds an efficient publish-subscribe system based on such community structures. BUBBLE[14] also creates communities based on encountering frequencies. It forwards a message first to nodes that can frequently meet its destination community and then to nodes that can frequently meet nodes in the destination community. The work in[15] adopts interest and connectivity for relay selection in a publish-subscribe system. It selects the node that meets the interest category of the destination frequently and has a high connectivity as the relay node. Wu *et al.* utilize the concept of home community, i.e., where a node frequently visits, to spread a message first to all communities and then to other nodes effectively in the network. In SMART,[5] each node builds a social map to record its understanding of the nearby social network and always forwards a message to nodes having closer social similarity with its destination.

3. SYSTEM DESIGN

In this section, we first introduce the overview and background of the proposed SocMessaging system. Then, we present the detailed design.

3.1 System Overview and Background

The SocMessaging system is designed as a social-based cyber-physical system for distributed message transmission in a local area, e.g., campus. Therefore, we assume that each user is associated with one mobile device that has short-range wireless communication capability, e.g., WiFi and Bluetooth. Figure 1 gives an overview of the SocMessaging system. The SocMessaging agent software is installed on each device and is responsible for message handling and transmission. Users can generate messages for other users through the agent. When devices are within the communication range of each other, the SocMessaging agents can communicate with each other to exchange and deliver messages. The agent of the destination node of each message also renders it on the device screen for user access. Since this paper focuses on system design, we leave the details on the short range wireless communication to future work. It is worthwhile to note that the designed SocMessaging system can realize not only the message transmission but also the information exchange among users in any potential applications distributively without the support from the infrastructure based network.

3.2 Message Generation

The message in SocMessaging is a user generated data tuple with four elements: *des*, *time*, *content*, and *TTL* (Time To Live). The former two elements represent the destination node ID of the message and the message generation time, respectively. The last two elements contain the content of the message and the maximal amount of time the message can live in the system. After its TTL expires, a message is deleted from the system even though it has not been delivered to its destination. Since nodes move continuously in the network, the communication opportunity during an encountering often is transient. Therefore, the size of each message is limited to ensure that a single message can be successfully transmitted in one encountering. A large message can be split into several small messages that satisfy the size limitation. The system administrator can decide the size limit based on node mobility in the network. The more frequently nodes move, the smaller the size limit should be.

3.3 Social Community

People in a local area often belong to certain social communities, and people in one community are more likely to meet with each other than with others outside the community. For example, PhD students in one department often meet in the department building and colleagues working in the same building are more like to meet with each other. This means that social community can represent future encountering probability to a certain extent. Therefore, such social community structure is exploited for efficient message transmission in SocMessaging, which will be introduced in Section 3.4.2.

The SocMessaging system creates communities by clustering nodes that can meet each other frequently. This can be completed by analyzing the encountering records of users. One common method is the k-clique community detection algorithm.[14] In this method, each node is regarded as a vertex in the graph representing the network, and two nodes with meeting frequency larger than a threshold is regarded connected in the graph. Then, a community is defined as the union of all k-cliques that can be reached from each other. The SocMessaging system can also use the method in[4] to detect social communities distributively.

3.4 Message Transmission

In SocMessaging, messages are relayed by nodes to gradually reach their destinations. As mentioned in the introduction section (Section 1), SocMessaging exploits both past encountering records and social networks to select relay node that is more likely to deliver a message to its destination. In this section, we first introduce how encountering records and social networks are exploited in SocMessaging. Then, we further present the details of the relay node selection in the message transmission process.

3.4.1 Encountering Probability

Considering that people usually move with a certain pattern, the past encountering frequency can be used to predict future encountering probability. Therefore, each node in SocMessaging maintains its future encountering probability with every other node based on previous encountering for the purpose of relay node selection. Specifically, following the method in,[6] when a node, say N_i, meets another node, say N_j, at the t-th time slot, its meeting probability with node N_j, denoted by $p_{ij}(t)$, is updated by the following equation:

$$p_{ij}(t) = p_{ij}(t-1) + (1 - p_{ij}(t-1)) * p_s \tag{1}$$

where $p_s \in [0, 1]$ is a fixed constant. The meeting probability also ages over time. At the end of the t-th time slot, $p_{ij}(t)$ is updated by

$$p_{ij}(t) = p_{ij}(t) * \beta \tag{2}$$

where $\beta \in (0, 1)$ is the aging constant. We introduce how to use the maintained meeting probabilities to evaluate a node's suitability as a relay node later in Section 3.4.3.

3.4.2 Social Closeness

In SocMessaging, a node's social closeness with another node, say N_j, is defined as its ability to meet nodes in N_j's social community. This is because nodes in one community are more likely to meet with each other. Then, the node with a high social closeness with N_j can help relay the messages for N_j to nodes that can easily meet N_j. Specifically, suppose node N_j belongs to social community C_k, node N_i's social closeness with N_j at the t-th time slot, denoted by $s_{ij}(t)$, is calculated by:

$$s_{ij}(t) = \frac{M_{ik}(t)}{V_k}, \tag{3}$$

where $M_{ik}(t)$ is the average number of nodes in community C_k that N_i can meet in a time slot and V_k is the size of community C_k. Note that $M_{ik}(t)$ is an averaged value calculated based on the encountering records in all previous t time slots. As a result, the larger N_i's social closeness with N_j is, the more likely that it can meet nodes in N_j's social community. We introduce how to use the social closeness to evaluate a node's suitability as a relay node later in Section 3.4.3.

3.4.3 Relaying Capability

As discussed in the previous two subsections, a node's encountering probability with another node denotes its ability to directly meet the node, while its social closeness denotes its ability to meet the node's social community. Both abilities are useful in determining a suitable relay node for a message. When all nearby nodes have low direct encountering probabilities with the destination of a message, the social closeness can help find nodes to deliver the message to the social community of the destination. When a message arrives at the social community of the destination, most nearby nodes have high social closeness with the destination. In this case, the encountering probability can help select the node that can meet the destination most frequently as the relay node. Therefore, we define a node's relaying capability to represent how suitable it can be the relay node by considering both the encountering probability and social closeness. Specifically, node N_i's relaying capability for destination node N_j at the t-th time slot, denoted by RC_{ij}, is calculated by

$$RC_{ij}(t) = \alpha p_{ij}(t) + (1 - \alpha) s_{ij}(t) \tag{4}$$

where $p_{ij}(t)$ and $s_{ij}(t)$ refer to N_i's encountering probability and social closeness with N_j, respectively. Also, $\alpha \in [0, 1]$ is a weighting factor. It is configured by the system administrator. Then, each node maintains its relaying capabilities for all other nodes for relay node selection in message transmission.

3.4.4 Relay Node Selection and Message Exchange

The relay node selection process is based on the definition of the node relaying capability. Each node always transmits its message to the neighbor node with the highest relaying capability to the message's destination. When no such a neighbor is available, the node simply holds the message until it meets a node with higher relaying capability to the destination

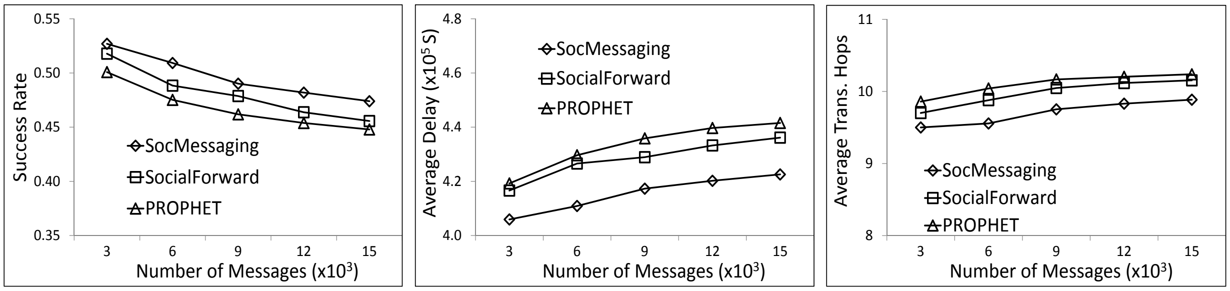
Specifically, when two nodes meet each other, each node first queries the other node its relaying capabilities for the destinations of messages on it. Then, each node creates a message transmission list containing messages for destinations for which the other node has higher relaying capability. It also ranks messages in the list based on the increase of the relaying capability if they are forwarded to the other node. Then, each node transmits its messages in a top-down manner to the other node until the list is empty or the communication opportunity ends.

4. PERFORMANCE EVALUATION

We conducted event-driven experiments to evaluate the performance of the SocMessaging system with the real trace from the MIT Reality project.[17] In this project, 94 iMotes were distributed to students/scholars in MIT to collect their encountering record. In the test, the first 1/3 of the trace was used as the initialization period, after which messages were evenly generated in the remaining time of trace. The total number of messages was varied from 3,000 to 15,000. Each message has randomly selected generator and destination. The TTL of each message was set to 1 week. The memory on each node is limited to the size of 100 messages.

We compared SocMessaging with an encounter record based method, i.e., PROPHET,[6] and a purely social network based method, denoted by SocialForward. The SocialForward is a simplified version of BUBBLE method[14] that only utilizes the meeting frequency with the destination community for relay selection. In this test, we measured three metrics: success rate, average delay, and average transmission hops. Success rate is the percentage of messages that have been successfully delivered to their destinations. Average delay is the average delay of all messages. Average transmission hops is the average transmission hops of all messages. The delay of an unsuccessful message is regarded as the TTL, and its transmission hops is regarded as 15, which is the maximal value observed in the test.

Figures 2(a), 2(b), 2(c) show the test results on the three metrics versus the number of messages, respectively. We see from the figures that SocMessaging leads to the highest success rate, the lowest average delay, and



(a) Success rate. (b) Average delay. (c) Average transmission hops.

Figure 2: Performance of each method with the MIT Reality trace.

the smallest average transmission hops. SocialForward has higher success rate, lower average delay and lower transmission hops than PROPHET. PROPHET presents lower performance than SocialForward because the number of nodes that can frequently meet a destination node often is limited. Therefore, when only using the direct encountering probability for relay selection, many messages cannot be forwarded to nodes that can meet their destination nodes and are dropped due to TTL, leading to a low performance. SocialForward utilizes the social closeness to select the relay node. As a result, messages are distributed to more nodes and are steadily forwarded towards their destinations, leading to higher performance than PROPHET.

SocMessaging leads to the best performance because it considers both encountering probability and social closeness for relay node selection, which can effectively solve the drawbacks of SocialForward and PROPHET. When neighbor nodes that can frequently meet the destination node of a message cannot be found, the considering of social closeness helps transmit the message towards its destination. After the message arrives at the community of the destination, the encountering probability helps find the node that is most likely to meet the destination. Consequently, messages can be quickly forwarded to their destinations. Such a result demonstrates the efficiency of the proposed SocMessaging system.

5. CONCLUSIONS

In this paper, we propose a social-based cyber-physical system for distributed message transmission among mobile device users, called SocMessaging. The SocMessaging system exploits the communication opportunities created by the encountering among mobile devices (i.e., people) to exchange and deliver messages without the support of the infrastructure based network. The key of the SocMessaging system is a message relay node selection algorithm. When selecting the relay node for a message, SocMessaging considers both the future meeting probability and the social closeness with the message's destination node and chooses the node that is more likely to meet the destination as the relay node. As a result, each message is gradually transmitted to its destination node. Finally, real-trace based experiments demonstrate the efficiency of the proposed system. In the future, we plan to investigate how to dynamically adjust the weight in calculating the relaying capability to further improve the message transmission efficiency.

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