Friendships in the Air: Integrating Social Links into Wireless Network Modeling, Routing, and Analysis

Zhuo Lu
Department of Computer Science
University of Memphis, TN, 38152
Email: zhuo.lu@memphis.edu

Yalin Sagduyu and Yi Shi
Intelligent Automation Inc.
Rockville MD, 20855
Emails: {ysagduyu, yshi}@i-a-i.com

***Abstract*—Social connections among network users have been well investigated as an additional opportunity in network design, such as in routing strategies and trusted networking. This paper presents a paradigm shift that explores the design and performance analysis of combining social links jointly with communication links to support message delivery in wireless networks. In a combined social and communication network, communication links are based on conventional wireless technologies (e.g., WiFi, Bluetooth) and social links are overlaid over a communication infrastructure (e.g., cellular network) that provides a complementary way for data transmission. The goal is to characterize the performance analytically when routing is designed by combining social and communication links. A distance discretization technique is applied to model the reliability and delay of the end-to-end message delivery, and a testbed is implemented with actual radios and real-world social network datasets to measure the performance of a heterogeneous network with social and communication links. The results presented via analysis and testbed experiments provide important insights on message delivery in a combined social and communication network and the developed analytical foundation enables network inference to improve the performance of message delivery.**

***Index Terms*—Heterogeneous network; wireless networks; social networks; routing; delay; reliability.**

I. INTRODUCTION

Leveraging social relationships to improve the network performance has been recently investigated in network routing protocol design, such as social-aware routing in delay-tolerant networks [1]–[6]. In these protocols, social ties are typically used as abstract or conceptual links for a node's decision making in routing. A social network can be considered not only as a logic topology that represents social connections used for decision making, but also as an overlay network over a physical infrastructure for information delivery. For example, when people make phone calls to their friends, they communicate with each other because they have social links and the cellular network infrastructure serves as the underlying communication medium for such social links. Social communication can also be performed over online social networks. For example, a person reads his/her friend's posts, where Internet is an underlying communication medium. Alternatively, social links may correspond to long-range communications, such as achieved with a relay (e.g., airborne gateway, unmanned aerial vehicle or satellite) or an increase in transmit power, and while they introduce additional challenges, such as interference and complexity, their successful use can be justified by the presence of underlying social relationships.

Today's networks feature a heterogeneous architecture, in which messages can be sent via social links or peer-to-peer communication links. For example, in cellular networks, social links on top of the 3G/4G infrastructure constitute an overlay network, and at the same time WiFi or Bluetooth links of smart phones form a conventional wireless network with peer-to-peer communication. Current routing and data delivery processes, by default, operate over one network interface (e.g., web surfing in smart phones through either the WiFi or cellular network interface). If network design jointly takes the overlaid social links and the conventional communication links into account, the network performance can be potentially improved with more reliable end-to-end delivery, higher throughput, or smaller message delay.

There are important applications for such a joint design, e.g., (i) emergency broadcast in which a node broadcasts some emergency message via every link. In this case, computing the minimum delay to reach a certain node requires jointly considering social and communication links. (ii) communication via trusted links for key exchange, in which secret keys can only be transmitted over trusted links. In this case, social links are regarded as trusted links, and at the same time neighbors in one-hop distance via communication links can also be trusted since neighbors can observe each other, and authenticate each other from the reciprocal channel property [7], [8]. Thus, for a node aiming to send a secret key to another node, it will attempt to find the shortest path via both social and communication links to minimize the delivery delay.

There have been few studies on routing (with local information only) in a social network [9] and this has been extended to a combined network with both social and communication links [10]. The typical assumption for analytical foundations in these works is that there exist an infinite number of users in a finite area network such that greedy routing can be applied with the guarantee that there exists a next hop neighbor found towards the destination. Nonetheless, such an assumption does not hold in practice. There are two underexplored issues in modeling and evaluating a combined social and communication network with a finite number of nodes: 1) it is not clear how to analyze the performance of a practical network with a finite number of nodes, where message delivery may fail not only due to social or communication link failures, but also due to the absence of a next-hop node (closer to the destination); 2) existing schemes (either social aware routing heuristics or combined network analysis with an infinite number of nodes) were validated in simulations only, but it is unknown how routing will perform in a real-time system with actual radios and realistic social relationships.

In this paper, we aim to address the above two issues from a network science perspective. In particular, we are interested in modeling the performance of a combined social and communication network with a finite number of nodes and implementing a real-world testbed to measure the real-time performance of combined social and communication network design. Our approach to analyze the performance of data delivery is based on a novel *distance discretization* technique, which gradually aggregates the delay or success probability of a message that reaches a discretized distance to the destination. Applying this approach, we model and analyze the delivery delay and success probability of a combined social and communication network with respect to a variety of network conditions, such as node density and link failure probability. In addition, a testbed is implemented to validate our analysis and further measure the performance of different routing strategies under various social and communication link setups in real-world scenarios.

Our contributions are three-fold: (i) we developed a novel network discretization technique to model the message delivery of combined social and communication networks; (ii) we implemented a testbed with actual radios and real-world social network datasets to measure the performance of combined social and communication networks; (iii) we presented both analytical and experimental results on message delivery performance in a combined social and communication network. Our results motivate the integration of social links into wireless network design to improve message delivery performance.

The reminder of this paper is organized as follows. In Section II, we introduce the preliminaries and models. In Section III, we present performance analysis of combined social and communication networks. In Section IV, we describe our testbed and experimental results. Finally, we conclude this paper in Section V.

II. PRELIMINARIES AND MODELS

In this section, we present assumptions and models, then formulate the problem of message delivery in a combined social and communication network.

A. Wireless and Social Network Models

We consider a combined social and communication network with a finite number of nodes, in which communication links are based on short-range wireless connections (e.g., WiFi, Bluetooth) and social links exist between two friends in a social network. A social link may connect two nodes beyond the one-hop short-range range (e.g., two friends communicate over long-range satellite and cellular networks). Both links can be used for data transmission. Hence, the combined social and communication network model differs from existing models [11]–[14] that leverage social links only for decision making in routing strategies.

Suppose that N static nodes are uniformly distributed on a disk area with radius R to form a combined social and communication network. Nodes can communicate using communication links if they are within each other's communication range r_c. Besides communication links, nodes can also communicate via social links. As a result, how nodes are connected via social links is essential for the performance of the combined social and communication network. It is well-known that social networks exhibit the small-world phenomenon, i.e., social actors are linked by short chains of acquaintances [15]–[17]. We adopt the Octopus model [9], [18] to capture such a phenomenon together with additional degree distribution characterization such as scale-free network properties.

In the Octopus model, there are short-range connection (SRC) and long-range connection (LRC) links to account for close and far social connections, respectively. In practice, social links may be coupled with communication links between nodes. For example, two socially close friends may be also geographically close to each other (e.g., friends living in the same apartment); then, they have both social and communication links. To accommodate such correlations, we use probabilities γ_{CS} and γ_{CL} to denote the probabilities that a SRC or LRC social link, respectively, corresponds to a communication link. Similarly, we denote by γ_{NCS} or γ_{NCL} the probabilities, respectively, that a SRC or LRC social link exists between two nodes without a communication link.

Fig. 1 shows an example of the combined social and communication network model: nodes B and C are within node A's transmission range. Therefore, there exist two communication links for node A: A $\leftrightarrow$ B, A $\leftrightarrow$ C. In addition, there exists a SRC social link with probability γ_{CS} between nodes A and B (or C). If the SRC link does not exist, there is a LRC social link with probability γ_{CL} between nodes A and B (or C). Consider nodes D and E in Fig. 1; because they are not within node A's wireless transmission range, there is no communication link from nodes A to D (or E). However, there still exists a SRC social link with probability γ_{NCS} between nodes A and D (or E). If the SRC link does not exist, there is a LRC social link with probability γ_{NCL} between nodes A and D (or E). In addition, we denote by β_s and β_c the social and communication link success ratios, respectively.

B. Greedy Routing and Procedure

In a combined social and communication network, a message can be transmitted over social or communication links along an end-to-end delivery path. We adopt the greedy routing mechanism [9], [10], [18], [19] for message delivery, as a viable solution over a multi-hop path using only local information at each node, which makes routing adaptive to a dynamically change network topology, where there exists no stable end-to-end path between two nodes.

A forwarding node under greedy routing always attempts to find the next-hop node in all of its social link and communica-

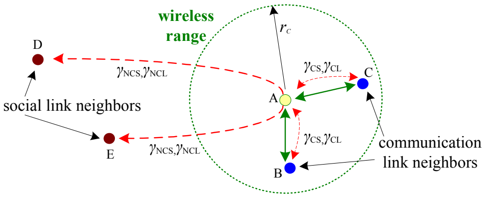

Fig. 1. Social and communication links of a node in a combined network.

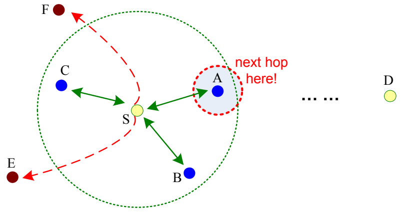

Fig. 2. Source S wants to deliver a message to destination D.

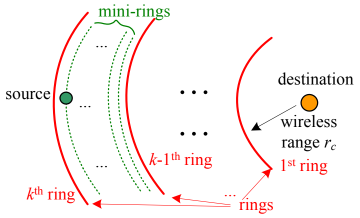

Fig. 3. The source-destination distance is divided by rings and mini-rings.

tion link neighbors, whose distance[1] to the destination is the shortest, and at the same time smaller than the forwarding node's distance to the destination. An example is shown in Fig. 2, where source S wants to transmit a message to destination D. It first checks its neighbors via both social links (nodes E and F) and communication links (nodes A, B, and C). Among all neighbors, it chooses the one that is closest to destination D, namely, node A in this case. Then, the message will be transmitted to node A, who will follow the same greedy routing procedure to find the next hop node. If nodes A and B do not exist in Fig. 2, node C would become the closest neighbor F to destination D. However, node F's distance to D is larger than source S's distance to D. This means that the message would be delivered farther to the destination, which is however not allowed by greedy routing. Therefore, source S would simply drop the message and claim delivery failure.

C. Problem Formulation

With network model and routing protocol defined, we are interested in evaluating the success probability and delay of message delivery in a combined social and communication network to analyze the benefit of a joint design for the routing protocol. To facilitate performance evaluation, we define the hop distance k between two nodes in the network as $k = \lceil d/r_c \rceil$, where d is their distance and r_c is the communication range. In this paper, we aim to evaluate the performance of a combined social and communication network in terms of the message delivery success probability S_k and average delivery delay T_k both as functions of hop distance k.

III. PERFORMANCE ANALYSIS AND EVALUATION

In this section, we derive the success probability and delay of end-to-end message delivery under greedy routing.

A. Performance under Greedy Routing

To facilitate tractable analysis, our methodology is to propose a new approximation technique called distance discretization: First, rings are drawn with radii r_c, $2r_c$, $\cdots$, centered around the destination as shown in Fig. 3. If the source has a hop distance k to the destination, it will fall between the $(k-1)$-th and k-th rings. Second, $n-1$ mini-rings are drawn with equal space $r'_c = r_c/n$ between adjacent rings. The mini-hop distance m between two nodes is defined as $m = \lceil d/r'_c \rceil$. Thus, if the source-destination hop distance is k, its mini-hop distance satisfies $(n-1)k + 1 \le m \le nk$.

The success probability S'_m is defined as the probability that message delivery is successful for a source-destination path with mini-hop distance $m \ge 1$, and the delivery delay T'_m is defined as the delivery delay for a source-destination path with mini-hop distance $m \ge 1$.

Given the complexity of combined social and communication networks, the direct derivation of S'_m (or T'_m) is mathematically intractable. Our approach is to derive a recursive solution to S'_m (or T'_m) that only includes the set of $\{S'_j\}_{1 \le j \le m-1}$ (or $\{T'_j\}_{1 \le j \le m-1}$) such that S'_m (or T'_m) can be computed numerically given any network setups.

1) Delivery Success Probability: We first compute S'_m. Suppose that a source has a message to send to its destination with mini-hop distance m. If $1 \le m \le n$ (i.e., the source is within one hop to the destination), the source can always send the message directly to the destination using the communication link. Thus, the delivery success probability is the communication link success ratio, i.e., $S'_m = \beta_c$ for $1 \le m \le n$.

Now consider the case of $m > n$. Under greedy routing, the source tries to find among its neighbors a next-hop node with the smallest mini-hop distance (to the destination) to forward the message. The next-hop node must have a mini-hop distance smaller than m. Let $Z_{m,j}$ denote the event that there exists a next hop node (via either communication or social link) that reduces the mini-hop distance by j $(1 \le j \le m)$, i.e., the message will be forwarded to a next-hop node with mini-hop distance $m-j$. The next-hop node will then use the same greedy routing strategy to forward the message. Thus, the delivery success probability from the next-hop node is S_{m-j}. Then we can write S'_m recursively as

$$S'_m = \begin{cases} \beta_c \sum_{j=1}^{n} \mathbb{P}(Z_{m,j}) S'_{m-j} + & \\ \quad \beta_s \sum_{j=n+1}^{m} \mathbb{P}(Z_{m,j}) S'_{m-j} & m \ge n+1 \\ \beta_c & 1 \le m \le n, \end{cases} \tag{1}$$

where $S'_0 = 1$ and $\mathbb{P}(e)$ is the probability of event e.

Next, we solve for $\mathbb{P}(Z_{m,j})$ in (1). We denote $E_{m,x}$ as the event that the forwarding node can find a node via either communication or social link that reduces the mini-hop distance by x, $(1 \le x \le m)$. Recall that $Z_{m,j}$ is the event that the next hop node reduces the mini-hop distance by j $(1 \le j \le m)$. Thus, event $Z_{m,j}$ is equivalent to the event that $E_{m,j}$ happens but at the same time $E_{m,j+1}$, $E_{m,j+2}$, $\cdots$, and

---

[1] In this paper, distance is referred to as the geographical or physical distance, not the social distance, unless specified otherwise.

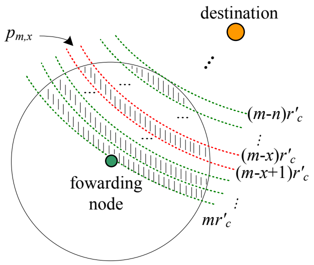

Fig. 4. Areas between mini-ring pairs inside the communication range.

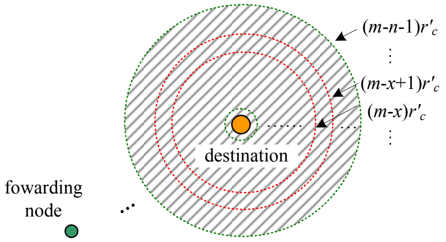

Fig. 5. Areas between mini-ring pairs outside the communication range.

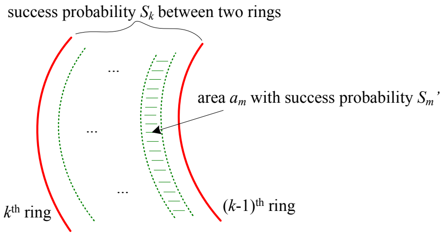

Fig. 6. Compute S_k from S'_m.

$E_{m,m}$ do not happen. Therefore, we can express $Z_{m,j}$ as

$$Z_{m,j} = E_{m,j} \cap \left(\cap_{x=j+1}^{m} E_{m,x}^{c}\right), \tag{2}$$

where $E_{m,x}^{c}$ denotes the complementary of event $E_{m,x}$, i.e., the event that $E_{m,x}$ does not happen. From (2), we have

$$\begin{aligned} \mathbb{P}(Z_{m,j}) &= \mathbb{P}\left(E_{m,j} \cap \left(\cap_{x=j+1}^{m} E_{m,x}^{c}\right)\right) \\ &= p_{m,j} \prod_{x=j+1}^{m} (1 - p_{m,x}), \end{aligned} \tag{3}$$

where $p_{m,x} = \mathbb{P}(E_{m,x})$.

Computing $p_{m,x}$ (i.e., the probability that the forwarding node with mini-hop distance m can find a node to reduce the mini-distance by x) consists of two parts in terms of hop distance: $1 \le x \le n$ and $n+1 \le x \le m$.

1) $1 \le x \le n$: $p_{m,x}$ is the probability that there exists a node in the shaded area between adjacent mini-rings $(m-x)r'_c$ and $(m-x+1)r'_c$, as shown in Fig. 4. We denote by $E_{m,x}^{\text{IN}}$ and $E_{m,x}^{\text{OUT}}$ the events that the forwarding node can find a node between adjacent mini-rings $(m-x)r'_c$ and $(m-x+1)r'_c$ in Fig. 4 that reduces the mini-hop distance by x inside and outside the transmission range, respectively. If event $E_{m,x}^{\text{IN}}$ happens, the node can be reached via communication link. To compute $E_{m,x}^{\text{IN}}$, we denote $p_1 = \mathbb{P}((E_{m,x}^{\text{IN}})^c)$ as the probability that there exists no node on the area between mini-rings $(m-x)r'_c$ and $(m-x+1)r'_c$, which can be computed via Poisson point process approximation [20] as

$$\begin{aligned} p_1 = \exp(-\lambda(&A((m-x+1)r'_c, nr'_c, mr'_c) \\ &-A((m-x)r'_c, nr'_c, mr'_c))). \end{aligned} \tag{4}$$

where $\lambda = N/(\pi R)^2$ is the node density on the network area, and $A((m-x+1)r'_c, nr'_c, mr'_c) - A((m-x)r'_c, nr'_c, mr'_c)$ is the area between mini-rings $(m-x)r'_c$ and $(m-x+1)r'_c$ inside the communication range, in which $A(r_a, r_b, d)$ is a function to compute the intersection area of two circles [21] with distance d that have radii r_a and r_b, respectively, satisfying

$$\begin{aligned} A(r_a, r_b, d) = r_a^2 \cos^{-1} \frac{r_a^2 + d^2 - r_b^2}{2dr_a} + \\ r_b^2 \cos^{-1} \frac{r_b^2 + d^2 - r_a^2}{2dr_b} - \\ \frac{\sqrt{(-d+r_a+r_b)(d-r_a+r_b)(d+r_a-r_b)(d+r_a+r_b)}}{2}. \end{aligned}$$

If event $E_{m,x}^{\text{OUT}}$ happens, the node can be only reached via social link. In the combined social and communication network, two nodes are socially connected with some probability ρ. This probability can be computed based on the social-communication link correlation model in Section II, i.e.,

$$\rho = \gamma_{\text{NCS}} + (1 - \gamma_{\text{NCS}})\gamma_{\text{NCS}}. \tag{5}$$

We denote by $p_2 = \mathbb{P}((E_{m,x}^{\text{OUT}})^c)$ the probability that there exists no node on the area between mini-rings $(m-x)r'_c$ and $(m-x+1)r'_c$ outside the communication range. Using the Poisson point process approximation and the thinning theorem [20], we can express p_2 as

$$\begin{aligned} p_2 = \exp(-\rho\lambda((2(m-x)+1)\pi r_c'^2 - A((m-x+1)r'_c, \\ nr'_c, mr'_c) + A((m-x)r'_c, nr'_c, mr'_c))). \end{aligned} \tag{6}$$

It follows from (4) and (6) that

$$p_{m,x} = 1 - \mathbb{P}((E_{m,x}^{\text{IN}})^c)\mathbb{P}((E_{m,x}^{\text{OUT}})^c) = 1 - p_1 p_2. \tag{7}$$

2) $n+1 \le x \le m$: We consider two cases that $x = m$ and $n+1 \le x < m$. If $x = m$, $p_{m,x}$ is the probability that the forwarding node is socially connected to the destination. Then, we have $p_{m,x} = \rho$ given in (5). If $n+1 \le x < m$, $p_{m,x}$ is the probability that there exists a node in the shaded area between mini-rings $(m-x)r'_c$ and $(m-x+1)r'_c$, as shown in Fig. 5. For a Poisson point process with density $\rho\lambda$ on the area, we obtain

$$p_{m,x} = 1 - e^{\rho\lambda\pi(2(m-x)+1)(r'_c)^2}. \tag{8}$$

In summary, we have the delivery success probability at mini-hop distance m as

$$S'_m = \begin{cases} \beta_c \sum_{j=1}^{n} \mathbb{P}(Z_{m,j}) S'_{m-j} + & \\ \quad \beta_s \sum_{j=n+1}^{m} \mathbb{P}(Z_{m,j}) S'_{m-j} & m \ge n+1 \\ \beta_c & 1 \le m \le n, \end{cases} \tag{9}$$

where the initial condition is $S'_0 = 1$, $\mathbb{P}(Z_{m,j}) = p_{m,j} \prod_{x=j+1}^{m}(1 - p_{m,x})$,

$$p_{m,x} = \begin{cases} 1 - p_1 p_2 & 1 \le x \le n \\ 1 - e^{\rho\lambda\pi(2(m-x)+1)(r'_c)^2} & n+1 \le x < m \\ \rho & x = m, \end{cases}$$

$\rho = \gamma_{\text{NCS}} + (1 - \gamma_{\text{NCS}})\gamma_{\text{NCS}}$, and $\lambda = N/(\pi R)^2$. Accordingly, as shown in Fig. 6, the success probability S_k at hop distance k can be computed from mini-hop distance S'_m as $S_k = \frac{\sum_{m=(k-1)n+1}^{kn} a_m S'_m}{\pi(2k-1)r_c^2}$, where a_m is the area between the $(m-1)$-th and m-th mini-rings, satisfying $a_m = (2m-1)r_c'^2$.

2) Delivery Delay: Next, we proceed to derive the average delivery delay T'_m. We denote by A_m the event that message delivery at the m mini-hop distance is successful. Then, $\mathbb{P}(A_m)$ is the delivery success probability and it is given in (9). Conditioned on event A_m, the average m mini-hop distance delay is expressed in a recursive way as

$$T'_m = \sum_{j=1}^{m} \mathbb{P}(Z_{m,j}|A_m)(D_j + T'_{m-j}), \tag{10}$$

where the initial condition is $T'_0 = 0$, D_j is the delay over j hops, satisfying

$$D_j = \begin{cases} D_c(\text{communication link delay}) & j \leq n \\ D_s(\text{social link delay}) & j > n, \end{cases} \tag{11}$$

and

$$\begin{aligned} &\mathbb{P}(Z_{m,j}|A_m) = \mathbb{P}(Z_{m,j} \cap A_m)/\mathbb{P}(A_m) \\ &= \mathbb{P}(Z_{m,j} \cap ((B_{m,j} \cap Z_{m,j} \cap A_{m-j}) \cup \\ &\quad (\cap_{k=1,k\neq j}^{m}(B_{m,k} \cap Z_{m,k} \cap A_{m-k}))))/\mathbb{P}(A_m) \\ &= \mathbb{P}(B_{m,j})P(Z_{m,j})P(A_{m-j})/\mathbb{P}(A_m). \end{aligned} \tag{12}$$

In (12), $B_{m,j}$ is the event that the link from the node with mini-hop distance m to the node with mini-hop distance $m-j$ does not fail. It follows from (10) and (12) that

$$\begin{aligned} T'_m = {} & \beta_c \sum_{j=1}^{n} \frac{(\mathbb{P}(Z_{m,j})S'_{m-j}}{S'_m}(D_c + T'_{m-j}) \\ & + \beta_s \sum_{j=n+1}^{m} \frac{\mathbb{P}(Z_{m,j})S'_{m-j}}{S'_m}(D_s + T'_{m-j}). \end{aligned} \tag{13}$$

Then, the average delivery delay T_k at hop distance k can be computed from mini-hop distance delay T'_m as $T_k = \frac{\sum_{m=(k-1)n+1}^{kn} a_m T'_m}{\pi(2k-1)r_c^2}$, where a_m is the area between the $(m$–$1)$-th and m-th mini-rings, satisfying $a_m = (2m-1)r_c'^2$.

Consequently, the delivery success probability and delay can be computed by (9) and (13), respectively. Note that (9) and (13) are based on the distance discretization technique, which separates the distance between two nodes into mini-rings with space r_c/n, as shown in Fig. 3. It is expected that the best approximation is achieved when $n \to \infty$ (i.e., the number of mini-rings used to discretize the distance goes to infinity).

IV. REAL-WORLD TESTBED AND EXPERIMENTS

In this section, we set up a testbed to measure the performance of the combined social and communication network under greedy routing and its improved versions. The testbed consists of programmable WiFi radios, RouterStation Pros [22], that represent network nodes, an Ethernet switch, and a high-fidelity wireless channel emulator, RFNest [23].

A. System Setup

Each node has one WiFi interface as the wireless communication link. IEEE 802.11b/g is used for radio MAC. All nodes are connected via (radio frequency) RF cables to the channel emulator that can attenuate realistic RF signals according to any specific network topology. They are also connected via Ethernet cables to an Ethernet switch to emulate the social links. A social network server is also connected with the switch. Any message transmitted over a social link will go to the server first, then be forwarded to the next hop. Thus, the social link delay and failures are emulated at the social server to accommodate various social network and link conditions. During our experiments, the total number of nodes is set to be 21 due to current hardware configurations.

We use the Reality Mining dataset [24] to generate social connections between nodes in the testbed. We use the data of 21 individuals with the largest number of friends. We also use the network connectivity data in Reality Mining dataset to set up the wireless network topology in the channel emulator.

B. Performance of Greedy Routing

We measure success probability and delivery delay in Figs. 7 and 9, respectively. Fig. 7 shows that as the hop distance increases, the success probability first sharply decreases then converges. If the social link is more reliable with low link failure probability, the end-to-end success probability increases. When the hop distance increases, the success probability also slightly increases. This means that under greedy routing, farther nodes may have larger success probability than closer nodes for message delivery to the destination.

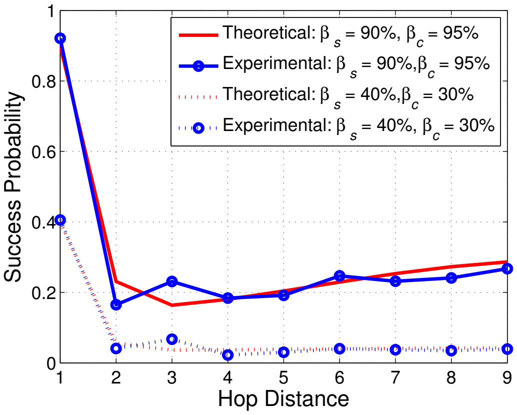

Fig. 7. Measurements of success probability with different communication and social link failures.

As Fig. 7 shows, the success probability slightly increases when the hop distance increases. This indicates that larger distance between two nodes increases delivery reliability. The reason behind this apparently counter-intuitive result is that greedy routing always attempts to move a message closer to the destination. However, a closer node is less likely to find a next hop with a social link to the destination. An example is shown in Fig. 8, where node 1 is closer than node 2 to the destination. Under greedy routing, they will examine if there exist neighbors (as potential next hop nodes) in areas A and B, respectively. However, area B is larger than area A. This means that node 2 is more likely to find a node through the communication link as the next hop that has a social link directly to the destination. As a result, Fig. 7 demonstrates that as the hop distance increases, the success probability sometimes slightly increases in experiments.

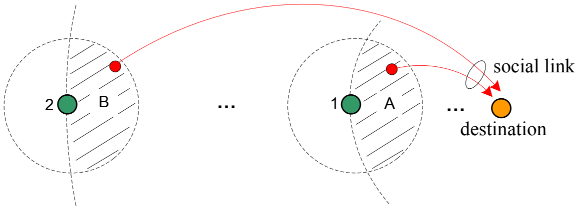

Fig. 8. Distant node is more likely to find through the communication link a next hop that has a direct social link to the destination under greedy routing.

Fig. 9 shows the delivery delay as a function of hop distance. The delay does not increase linearly as hop distance increases, but starts to converge when hop distance is large, because a node can always have a chance to find a social link that reduces the hop distance larger than 1. Figs. 7 and 9 show a reasonable match between the theoretical analysis and experimental results. For example, the maximum derivation for success probability is 20.1% at hop distance $d = 3$ and the average deviation is 9.3%. Therefore, our modeling provides a good prediction for the performance of real-time systems.

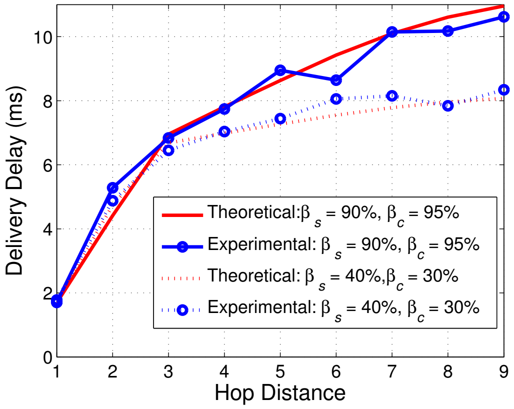

Fig. 9. Measurements of delivery delay with different communication and social link failures.

V. CONCLUSION

In this paper, we systematically studied the performance of combined social and communication networks with a finite number of nodes. We proposed a distance discretization technique to derive the success probability and delay of message delivery. We built a testbed and conducted a variety of experiments on the testbed to measure the performance of social and communication networks. Our studies showed that adequately combining social links with wireless network design can substantially benefit network communications in many perspectives (e.g., delay and reliability). Today's network infrastructures provide an underlying architecture that overlays social networks over wireless communication medium. Therefore, combined social and communication design for data delivery is a promising technique for network performance optimization.

REFERENCES

[1] Q. Li, S. Zhu, and G. Cao, "Routing in socially selfish delay tolerant networks," in *Proc. of IEEE INFOCOM*, Mar. 2010.

[2] S. Trifunovic, F. Legendre, and C. Anastasiades, "Social trust in opportunistic networks," in *Proc. of IEEE INFOCOM*, Mar. 2010.

[3] K. Wei, X. Liang, and K. Xu, "A survey of social-aware routing protocols in delay tolerant networks: Applications, taxonomy and design-related issues," *IEEE Communications Surveys & Tutorials*, vol. 16, 2014.

[4] K. Chen and H. Shen, "SMART: Lightweight distributed social map based routing in delay tolerant networks," in *Proc. of IEEE ICNP*, 2012.

[5] Z. Li and H. Shen, "Social-P2P: Social network-based P2P file sharing system," in *Proc. of IEEE ICNP*, 2012.

[6] M. W. Bigrigg, K. M. Carley, K. Manousakis, and A. McAuley, "Routing through an integrated communication and social network," in *Proc. of MILCOM*, 2009.

[7] S. Mathur, W. Trappe, N. Mandayam, C. Ye, and A. Reznik, "Radio-telepathy: extracting a secret key from an unauthenticated wireless channel," in *Proc. of ACM Mobicom*, 2008.

[8] C. Chen and M. A. Jensen, "Secret key establishment using temporally and spatially correlated wireless channel coefficients," in *IEEE Trans. Mobile Computing*, vol. 10, 2011, pp. 205–215.

[9] H. Inaltekin, M. Chiang, and H. Poor, "Delay of social search on small-world random geometric graphs," *J. Mathematical Sociology*, 2012.

[10] K. Neema, Y. E. Sagduyu, and Y. Shi, "Search delay and success in combined social and communication networks," in *Proc. of IEEE Globecom*, 2013.

[11] A. Mei, G. Morabito, P. Santi, and J. Stefa, "Social-aware stateless forwarding in pocket switched networks," in *Proc. of IEEE INFOCOM*, 2011.

[12] J. Wu and Y. Wang, "Social feature-based multi-path routing in delay tolerant networks," in *Proc. of IEEE INFOCOM*, 2012.

[13] X. Lin, R. Lu, X. Liang, and X. Shen, "STAP: A social-tier-assisted packet forwarding protocol for achieving receiver-location privacy preservation in VANETs," in *Proc. of IEEE INFOCOM*, 2011.

[14] P. Costa, C. Mascolo, M. Musolesi, and G. P. Picco, "Socially-aware routing for publish-subscribe in delay-tolerant mobile ad hoc networks," *IEEE J. Selected Areas in Communications*, vol. 26, pp. 748–760, 2008.

[15] A. L. Barabasi and R. Albert, "Emergence of scaling in random networks," *Science*, vol. 286, pp. 509–512, 1999.

[16] D. J. Watts and S. H. Strogatz, "Collective dynamics of small-world networks," *Nature*, vol. 393, pp. 440–442, 1998.

[17] S. Schnettler, "A structured overview of 50 years of small-world research," *Social Networks*, vol. 31, pp. 165–178, 2009.

[18] M. C. H. Inaltekin and H. V. Poor, "Average message delivery time for small-world networks in the continuum limit," *IEEE Trans. Information Theory*, vol. 56, pp. 4447–4470, 2010.

[19] J. M. Kleinberg, "Navigation in the small world," *Science*, 2000.

[20] M. Penrose, *Random Geometric Graphs*. Oxford Univ. Press, 2003.

[21] Circle-Circle Intersection, http://mathworld.wolfram.com/Circle-CircleIntersection.html.

[22] Router Station Pro - Ubiquiti networks, http://www.ubnt.com/routerstation.

[23] Z. Lu, Y. Sagduyu, and Y. Shi, "Socio-technological communication testbed for mobile social networks," in *Prof. of MILCOM*, 2014.

[24] MIT RealityMining Dataset, http://realitycommons.media.mit.edu/realitymining.html.