Bridging Intermittently Connected Mobile Ad hoc Networks (ICMAN) with Sociological Orbits

Joy Ghosh
Computer Science and Engineering
State University of New York at Buffalo
joyghosh@cse.buffalo.edu

Cedric Westphal
Nokia Research Center
Mountain View, CA
cedric.westphal@nokia.com

Hung Ngo, Chunming Qiao
Computer Science and Engineering
State University of New York at Buffalo
{hungngo, qiao}@cse.buffalo.edu

I. Introduction

An Intermittently Connected Network (ICN) is often modeled as a weighted graph, where the capacities and durations of edges (radio links) between nodes (users) are time varying due to user mobility. As such, there is no guarantee of a contemporaneous end-to-end path from the source to the destination through intermediary peers. This sets an ICN [1] strictly apart from a conventional mobile ad hoc network (MANET). Consequently, traditional MANET routing protocols are rendered useless within ICN.

Earlier work [15] on temporally disconnected networks proposed intelligent means of data dissemination, which led to various other propositions based on similar concepts. More recent research within ICN [9] has considered algorithms based on deterministic user mobility, which is neither applicable to MANET, nor to ICMAN. Literature suggests similar study on how mobility (controlled or not) affects routing protocols and network performance (e.g., network capacity) in various types of ad hoc networks including sensor networks with mobile sinks (or base stations), and delay tolerant networks [1], [6], [13], [18]. However, they did not deal with specific user mobility patterns. In [8], [10], [11], [14], the main focus was on the so-called "contact probability" of two users, which is oblivious to the specific locations (or "hubs") they visit.

In this work, we focus on Intermittently Connected Mobile Ad hoc Networks (ICMAN), which lacks infrastructure like a MANET, in addition to having non-deterministic user mobility like in an ICN. In [3] we studied wireless users' mobility traces in ETH Zurich campus to validate our sociological orbital claims in [4], [5]. We found that users regularly visit a small set of socially significant places (called "hubs") forming a "hub list" and showed that such hub lists may be clustered via a technique involving a *Mixture of Bernoulli distributions*. We shall refer to such clusters that is represented by a hub list along with its associated visit probabilities as a "mobility profile" and shall use these profiles to propose efficient routing solutions for ICMAN users. For a conventional MANET (as opposed to intermittently connected networks), we proposed efficient routing solutions [4], [5] that leveraged on our concept of "sociological orbits" in the mobility patterns of wireless users. In this work, we illustrate the usefulness of our mobility profiles in also performing "hub-level" routing within an ICMAN, where a message from a source hub to a destination hub may be delivered only if the source or, other intermediary peers carrying the message, move into the destination hub. Note that this assumption differs from our earlier work [4], [5] where we assumed sufficient number of intermediary peers for "greedy geographic forwarding" [12] to take place.

[1] also referred to as Delay Tolerant Networks

According to our findings in [3], we consider an ICMAN where each user may have a list of hubs to visit such that each user may stay in its current hub for some time before moving to another hub in the list with a certain probability. We propose a sociological orbit aware location approximation and routing (SOLAR) protocol called *SOLAR-HUB* that is unique in taking advantage of user mobility profiles to perform "hub-level" routing. For comparison study, we also propose two different variations of multi-path SOLAR protocols *Static SOLAR-KSP* and *Dynamic SOLAR-KSP* that perform "user-level" routing based on user "contact probabilities" computed from our user mobility profiles, which makes them stand apart from the other existing contact probability based user-level routing strategies. We compare the performances of the different SOLAR protocols with that of the simple and efficient Epidemic routing [15] and show that all SOLAR protocols outperform Epidemic routing in terms of higher data throughput, lower network overhead, and lesser end-to-end data delay.

II. SOLAR Protocols

In this section, we shall describe our SOLAR protocols in more detail.

A. SOLAR-HUB Algorithm

In this "hub-level" routing protocol, users are assumed to know the next hub they are going to visit, in addition to every other user's mobility profile. The latter assumption is discussed in Section IV. When a user (source) wants to deliver data to another user (destination), it tries to forward data only to its own neighbors (at most k) with a higher delivery probability to the *hubs* visited by the destination, and not to the destination itself.

More specifically, when a source has data to send, it forwards a copy of the data packet to a maximum of $k/2$ neighbors with higher probability of visiting the "most visited" hub of the destination, and to a maximum of $k/2$ *different* neighbors with higher probability of visiting the "second most visited" hub of the destination. If no such neighbors exist, source caches the packet for a specified timeout period. In contrast, each downstream user only forwards a copy of the data packet to a maximum of k neighbors who have higher probabilities to visit the hub of the destination chosen by its upstream neighbor. To avoid loops, each downstream user that receives a packet in a particular hub, only repeats this forwarding process when it moves into a different hub. Once a packet reaches a user who is within either the most or, the second most visited hub of the destination, it is cached by that user for a specified timeout period for the destination user.

B. Static SOLAR-kSP Algorithm (S-SOLAR-KSP)

In this version of SOLAR, we assume that each user knows of every other user's mobility profiles. Every user then computes the *contact probability* with every other user, which may be computed in various ways as suggested in [8], [10], [11], [14]. In this work, we compute these probabilities by observing the simulated mobility traces. Next, the contact information between all users is represented by a weighted graph $G = (V, E)$, where V is the set of all the users, and E is the set of weighted edges between every pair of users that have at least one hub in common. Let $P(u, v)$ be the contact probability of users u and v. Then the weight of edge (u, v) is given by $w(u, v) = \log(1/P(u, v))$. In this weighted graph, each user applies a variation of the Dijkstra's Shortest Path algorithm [2] to find k shortest paths (kSP) to every other destination, such that each path has a different next hop user from the source. Each kSP then shall have a *delivery probability* for the respective pair of users via other intermediary peers, making it a "user-level" routing technique. A user only needs to maintain the next hops for each of the paths (maximum of k entries per destination user, referred to as N^{kSP}_{next}). When the source has a packet to send to a destination outside its radio range, it caches a copy of the packet for only a pre-determined time interval T, during which it may send copies of the packet to all users in N^{kSP}_{next} that come within radio range. Each downstream user in the path repeats this same process as that packet gets forwarded towards the destination.

C. Dynamic SOLAR-kSP Algorithm (D-SOLAR-KSP)

In this variation of SOLAR, each user not only computes kSP to every other user in the network similar to S-SOLAR-KSP, but also does so for all possible neighbors as a next hop. Additionally, at the time of forwarding, users forward to at most k users from amongst their current neighbors with higher delivery probability (pre-computed at start) to the destination and not only to users within N^{kSP}_{next}. To avoid packet duplication, when a user receives any packet in a hub, it waits till it moves to a new hub before repeating the forwarding process described above. Also, users are assumed to not communicate with any other user (except with the destination) when they travel from one hub to another. Thus, Dynamic SOLAR-kSP combines static hub based information with dynamic selection of next hop on the path towards the destination.

For comparing all the above protocols we empirically choose a value of $k = 2$ for each of them and only show those results due to the lack of space.

III. PERFORMANCE ANALYSIS

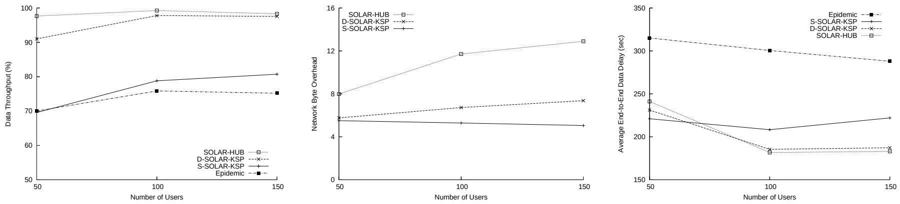
We simulated all our SOLAR protocols, along with the Epidemic [15] protocol using the GloMoSim network simulator [17]. We ran the simulation for $3,000$ seconds within a $1,000$ by $1,000$ square meter terrain, assuming a 802.11 MAC layer protocol with a practical radio range of 125 meters. Each user was assumed to have a cache size of 200 packets with a timeout of 400 seconds. A total of 15 hubs (each covering $2,500$ square meters) were assumed. Realistic speeds of 1 to 10 meters/second were assumed within hubs, and the inter-hub transition time was assumed to be exponential with a mean of 40 seconds.

Under these assumptions, we present here only the observed performance of the protocols with a CBR traffic (each payload is 1460 bytes) with varying number of users. Given a fixed terrain size and radio transmission range, the total number of users directly impact the network connectivity. As seen from Figure 1(a), SOLAR-HUB has the maximum throughput (i.e., $\frac{data\ packets\ received}{data\ packets\ generated}$), closely followed by D-SOLAR-KSP, while S-SOLAR-KSP and Epidemic have lower throughput. However, as seen in Figure 1(b), SOLAR-HUB is penalized in the cost of network byte overhead (i.e. $\frac{total\ bytes\ transmitted}{data\ packets\ received}$), whereas D-SOLAR-KSP and S-SOLAR-KSP have much lower overhead. Epidemic however performs 100 times as worse as SOLAR-HUB and had to be omitted from this graph. Figure 1(c) shows that SOLAR protocols not only have higher throughput and lower overhead than Epidemic, but also enjoy shorter end-to-end delays (i.e., time taken to locate a destination and deliver data). We have done extensive simulation study by varying several other parameters and have obtained similar results on all accounts, but are unable to present those results here for lack of space. Thus it is clear that mobility profile information can greatly enhance the performance of routing protocols within ICMAN over other non-mobility aware conventional approaches.

IV. NOTE ON MOBILITY PROFILE LIFETIME

A priori knowledge of the mobility profile for all users presents some scalability issues: each user can only maintain mobility profile information regarding a finite number of users. A solution to this problem is to have each user keep a buffer containing mobility profiles for a set number of users, and to flush out older mobility profiles as new ones are required.

In all the variants of SOLAR introduced here, if the source does not have the mobility profile of its intended correspondent, it can request it from its neighbors by issuing a profile request. The neighbors can then forward the request to their own neighbors if they do not possess the requested profile, or provide the profile if they do. In [16] it is shown that the



(a) Data Throughput (%) (b) Network Byte Overhead (c) End-to-End Data Delay (sec)

Fig. 1. Protocol Performance vs. Number of Users

probability to have a positive answer to the request depends on the length of time each profile is kept by a user and on the maximum number of hops the request is forwarded. It can be ensured that the request is satisfied with high probability by setting the maximum of hops to the right value. This shall be one direction of our future work.

V. Conclusion

Efficient routing within Intermittently Connected Networks (ICN) is specially daunting due to the unavailability of contemporaneous end-to-end path from a source to a destination through intermediary peers that renders most reactive and proactive routing protocols useless. Within ICNs researchers have either studied deterministic [9], or random mobility based protocols [14], [15] whereas we exploit semi-deterministic sociological mobility profile based routing. Others in [1], [7], [18] have also proposed methods to either exploit or influence the network mobility (e.g., by introducing and controlling the motion of foreign mobile agents) to improve network efficiency. However, foreign agents may not always be freely available and their ready deployment may not always be feasible.

In this paper, we apply our previously validated concepts of sociological orbits involving a set of socially significant places (or hubs) to propose *mobility profile* based efficient and unique "hub-level", as well as "user-level" routing solutions for within ICN. Our proposed mobility profiles may also be used in computing "contact probabilities" suggested as an useful technique to aid routing by other researchers in [8], [10], [11], [14]. We propose three *Sociological Orbit aware Location Approximation and Routing (SOLAR)* algorithms, that leverage upon our mobility profiles to route data within an ICMAN more efficiently than other conventional routing approaches (e.g., Epidemic routing [15]) in terms of higher data throughput, lower network overhead, and lesser end-to-end data delay. We have already established the simplicity and efficiency of using our SOLAR framework in a Mobile Ad Hoc Network (MANET) [4], [5]. In this work, we present equally strong results to prove that our proposed SOLAR is as strong a candidate of choice when it comes to meeting the challenges of routing within an ICMAN.

In future we aim to look at other issues such as optimization of multi-path in such networks and other dynamic (hub and kSP) routing solutions based on the knowledge of the next hub etc. In addition, we intend to study the effects of lifetime of mobility profile information on the routing efficiency.

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