Mobility Profile based Routing within Intermittently Connected Mobile Ad hoc Networks (ICMAN)

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ABSTRACT

Routing in Intermittently Connected Networks (ICN) is a challenging problem due to the time varying nature of network connectivity. In this work, we focus on a special class of ICN formed by mobile ad hoc users called ICMAN. A recent study of wireless users' mobility traces revealed that users usually move between a small set of socially significant places (called "hubs") to form so-called "sociological orbits" [6]. To exploit the knowledge about such mobility profiles, we propose a hub-level routing method, and two versions of user-level routing methods. We compare these approaches with Epidemic routing [21] to highlight the advantages of sociological orbit aware routing within ICMAN in terms of achieving a higher throughput and a lower overhead.

Categories and Subject Descriptors: C.2.2 Network Protocols: Routing protocols

General Terms: Algorithms, Design, Human Factors, Performance

Keywords: Mobility aware Routing protocols, Intermittently Connected Networks, Performance analysis

1. INTRODUCTION

An Intermittently Connected Network (ICN) may be modeled as a graph, where the capacities and durations of edges between nodes are time varying due to the mobility of users. An important characteristic of all ICNs (also referred to as Delay Tolerant Networks) that sets them apart from conventional mobile ad hoc networks (MANET) is the possibility that an end-to-end path via intermediary peers may not exist from a source to a destination at any one point in time. This renders the traditional MANET routing protocols inappropriate for ICN. Accordingly, routing in ICN has received significant interest from the research community recently.

In this work, we focus on Intermittently Connected Mobile Ad hoc Networks (ICMAN) formed by a group of mobile users roaming within a geographical area that is fairly large relative to the wireless transmission range, who either have no access to the infrastructure, or for other regulation or application specific requirements, could not or do not want to use the infrastructure for transferring certain delay tolerant data amongst themselves. In other words, the features of such ICMAN include those of ICN, as well as those of MANET such as lack of infrastructure, and non-deterministic mobility pattern of the users. We aim to develop routing protocols based on the findings of our recent study of wireless users' mobility traces [6], where we have shown that a user regularly visits a small set of socially significant and geographically distant places called "hubs". More specifically, we shall exploit the knowledge of the users' sociological hub based orbital mobility profiles in increasing routing protocols' throughput and decreasing their overhead.

Some earlier work on ICN in [8, 21] has led to various other propositions based on similar concepts. For example, the concept in [8] was extended upon by the authors in [16], where they proposed a probabilistic routing scheme whereby each user maintains the so-called "delivery predictability" to each known destination, and uses this metric to make routing decisions. Similarly, in [10, 12, 15, 19, 23], routing decisions were mainly based on the so-called "contact probability" of two users (or in case of having an infrastructure, the probability of one user visiting an access point). In particular, [11] has considered some algorithms to calculate the contact probability based on deterministic mobility of the users, which is suitable for satellites with fixed paths, or busses with fixed routes but is not applicable to an ICMAN having mobile users. There has also been effort in studying the use of mobile "agents" (with controlled mobility) to improve performance (e.g., network capacity) in ICN [4,18,26]. However, except a few "mobile agents", no specific mobility patterns of the users were considered. None of these existing works has considered how to take advantage of users' semi-deterministic, and partially-repetitive sociological hub based orbital movement patterns for efficient routing.

For a conventional MANET (as opposed to ICMAN), user mobility was shown to affect routing protocol performance in [2]. The work in [9] exploited user mobility in MANET as a type of multi-user diversity, and showed that user mobil-

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ity may actually help increase the theoretical capacity of a MANET. In addition, some research has also been done on MANET in [17, 20] to take advantage of mobility information obtained via continuous location tracking and mobility prediction within a small time scale and/or geographical distance (e.g., *within* a hub). We had earlier proposed efficient routing solutions for MANET in [7] under the framework of "sociological orbit aware location approximation and routing" (or SOLAR) by assuming sufficient number of "transient" users between two hubs to use geographical forwarding to route messages between hubs. None of the above work on MANET however, would apply to ICMAN. To the best of our knowledge, this paper is the first to exploit users' practical mobility profiles and in particular "hub" based routing concepts within ICMAN.

In accordance with the findings from our study of actual mobility traces, we consider an ICMAN where each user may have a list of hubs to visit with corresponding probabilities. Once in a hub, the user may stay there for a while before moving to another hub in the list with a certain probability. The distance between two hubs is larger than the wireless transmission range, and there is not enough "transient" users in between the two hubs to form a path from one hub to another. Accordingly, a message can go from one hub to another only when carried physically by a mobile user.

One of our main contributions of this work is a routing protocol called *SOLAR-HUB* that takes advantage of user mobility profiles to perform "hub-level" routing in such an ICMAN. With SOLAR-HUB, a message from a sender to a receiver will be routed to one or more hubs visited by the receiver called destination hub(s) either when the source or, an intermediate user carrying the message, moves into the destination hub(s) where the receiver can retrieve the message when it visits the same. Clearly such a hub-level routing differs from any contact-probability based routing in several aspects. First, one may compute the contact probability of two users based on all users' hub-visit probabilities (as described in our technical report [22]) but not vice versa (since most users' contact information is devoid of location information). Secondly, the concept of hub-based routing can be generalized such that a user may deliver a message to another by depositing the message to a destination hub(s) (containing a special storage device), even when the contact probability of the two users may be zero, which is possible when the two are never in the same hub at the same time (and there are no other intermediate users in the system).

In particular, we shall focus on a multi-path version of SOLAR-HUB, where a message is delivered to only two destination hubs ("most visited" and "second most visited") via up to k downstream neighbors of the source. In addition, we also propose two "user-level" routing protocols based on users' "contact probabilities" and k-shortest path (KSP) called *Static SOLAR-KSP* and *Dynamic SOLAR-KSP*. Unlike existing user-level routing protocols based on contact probabilities, however, they use the established mobility profiles of the users to compute the contact probabilities. As a result, they do not need to update the contact probability often which will reduce overhead and also can take advantage of the relatively longer period of stability of the KSP even in the presence of non-deterministic user mobility.

Finally, we compare the performances of these three SOLAR protocols with Epidemic Routing [21] to show that all SOLAR protocols outperform Epidemic Routing in terms of a higher data throughput, a lower network overhead, and a lower end-to-end data delay. In particular, both SOLAR-HUB and Dynamic SOLAR-KSP are shown to be especially promising for use in such ICMAN.

The rest of the paper is organized as follows. We first provide necessary background on the SOLAR framework in Section 2. In Section 3, we discuss the complexity of the problem of finding a multi-path routing algorithm in such a ICMAN that can maximize the delivery probability and point out an open problem. Such a discussion motivates our work on the heuristic routing algorithms like SOLAR-HUB, and Static and Dynamic SOLAR-KSP, which are described in Section 4. Results from the performance comparison among these routing algorithms and Epidemic Routing are presented in Section 5, and Section 6 concludes the paper.

2. THE SOLAR FRAMEWORK

In this section, we briefly describe and enhance the SOLAR framework we proposed in [7]. In the real world, it has been observed that users routinely spend a considerable amount of time at a few specific place(s), referred to as hub(s). For example, in a WLAN scenario, a hub may be a floor within a building or, the entire building itself, depending on the scale of the network model. Although it is hard (and may be even against privacy policies) to keep track of an individual at all times, one can still take advantage of the fact that most users' movements are within, and in between, a list of hubs, forming an inter-hub orbit (IHO).

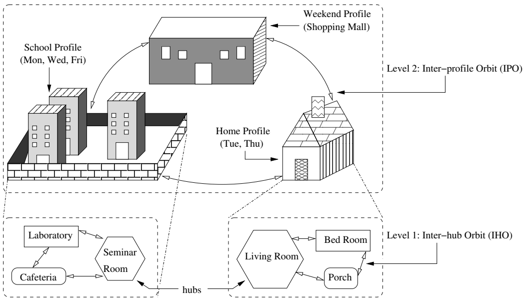

Figure 1: A hierarchical view of sociological orbits

Let us consider a graduate student who only has classes on Monday, Wednesday and Friday, when he is found on a school campus, spending most of his/her time in either his/her laboratory, a seminar room, or the cafeteria, each of which shall form a "hub" in this example (as shown in Figure 1). The actual list of hubs visited by the student on the same day is called a "hub list". Even if such hub lists may vary from one day to another, that variation is only marginal (as shown in [6]). In most cases, a number of hub lists visited by the student over a period of days may be clustered together and represented by a single "weighted hub list", where the weight associated with each hub denotes the probability of the student visiting that hub within that period. Such a weighted hub list then becomes the student's "Mobility Profile". If one wishes to locate the student on a school day, knowing this *School Profile* within the campus shall be helpful, where one can most probably find him/her in either the laboratory, or the seminar room, or the cafeteria, without having to look all over the campus.

As part of our recent work on validating the SOLAR framework, we have analyzed a year's worth of wireless users' mobility traces collected on the ETH Zurich campus. By using a clustering algorithm based on the *Bernoulli Mixture* model, we have shown that one can not only identify the mobility profile(s) of a wireless user, but also use the mobility profiles so derived to perform "hub-level" location predictions more accurately than using a general statistical approach based on hub-visit frequencies [6].

The mobility traces and results from the mobility profiling analysis lays down a solid foundation for the work to be described in the following sections. In particular, we will consider a practical orbital mobility model called *Probabilistic Orbit* where a user visits a list of hubs with certain probabilities according to his/her mobility profile. The parameters (and their values) used in our simulation studies of the performance of various protocols are also based on this model.

It is noted that although the mobility traces are for WLAN users on the ETH campus, they are indicative of the typical users in general and thus are also applicable to the ICMAN under consideration, especially when/if a group of these users also decide to form a ICMAN so that they can run certain applications which require the data (e.g., a huge file) be transferred not through the WLAN APs and the associated infrastructure, but through ICMAN. As a future work, we intend to collect and analyze the mobility traces of ordinary people and ultimately, set up an experimental ICMAN on which mobility traces of the ICMAN users can be collected and analyzed.

3. A NOTE ON COMPLEXITY OF DELIVERY PROBABILITY

A common objective of various (multi-path) routing algorithms we propose in this paper is to maximize the delivery probability from a source s to a destination d subject to various constraints including buffer sizes, cache time, network overheads, and/or maximum end-to-end delay.

Let G be a complete directed graph whose nodes represent the mobile users in the ICN under consideration. Fix a source s and a destination d. Let A denote a routing algorithm which aims to maximize the delivery probability from s to d subject to some constraints. The routing algorithm A forces packets to be delivered through a subset of edges of G.

Let $G(A)$ denote the subgraph of G induced by A, i.e. (u, v) is an edge of $G(A)$ if there is a possibility that u delivers a packet to v under A. For instance, if A is a naive broadcast strategy where each user delivers a packet it receives to all users it meets within a time interval T, then (u, v) is an edge of $G(A)$ if the probability that u meets v within T is positive. We will refer to $G(A)$ as the *delivery subgraph* associated with A.

More often than not, each edge of $G(A) = (V, E)$ is associated with an existence probability (the probability that the edge exists). For example, a sensible routing strategy is as follows. Given a fixed positive integer k, each user u in the network chooses at most k "down-stream" neighbors $v_1, \ldots, v_l$ $(l \leq k)$, i.e. $(u, v_i) \in E$, $\forall i = 1, \ldots, l$. The routing strategy is to start transmission from s, and every user receiving a new packet forwards the packet to all "available" neighbors among the k chosen ones. Here, "availability" may mean availability within some specific time interval T, or availability without time limit. Whatever notion of "availability" we choose, there is a probability p_e for each edge e to exist.

The delivery probability to be optimized is a function of $G(A)$ along with the existence probabilities p_e of the edges of $G(A)$. For the k-downstream neighbor example, the delivery probability is the probability that s is connected to d in $G(A)$. Let $p(G, A)$ denote this probability. The objective is to find an A that maximizes $p(G, A)$.

Unfortunately, computing the connectedness probability in a random graph is very hard (even for graphs with bounded degree like in our case). There is a vast literature on this problem. For example, Chapter 7 of [3] contains a partial set of references. It is unlikely that this probability is a simple function [14][1]. In essence, the optimization problem may even be harder than **NPO** (i.e., the class of optimization problems whose decision versions are in NP [1]).

Given this negative result, one can envision two general approaches:

- Find another function $p'(G, A)$ which approximates $p(G, A)$, yet $p'(G, A)$ is computable in polynomial time; then, find A that maximizes $p'(G, A)$. This approach shall be a major future research topic for us. For the present, we do not know of any good strategy to estimate $p(G, A)$ that is polynomial-time computable for general A.

- Find a routing strategy A for which $p(G, A)$ can reasonably be computed or estimated. This is the approach we will take for the rest of this paper. We will propose several heuristics to maximize the delivery probability and compare them with an existing routing algorithm.

4. PROPOSED SOLAR PROTOCOLS

In this section, we briefly describe the workings of each of the proposed SOLAR protocols suited for use within an ICMAN.

4.1 SOLAR-HUB Algorithm

In this hub-level routing protocol, users are assumed to know the next hub they are going to visit after they move out of their current hub, in addition to every other user's mobility profile. When the source user wants to deliver data to a destination user, it tries to forward data to up to k of its own neighbors that have a higher *delivery probability* to hub(s) visited by the destination, and not to the destination itself. Let us define a few terms:

- $P^d_{n_i h_j}$: The delivery probability of user n_i to hub h_j.

- $P^t_{n_i h_j}$: The probability of user n_i to travel to hub h_j ever during simulation.

- $h(n_i)$: The hub that user n_i is going to visit next

- $P^c_{n_i n_k}(h_j)$: The probability for contact of users n_i and n_k in hub h_j ever during simulation.

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[1] We thank Prof. Van H. Vu for communicating this result to us.

- $N(n_i)$: Neighbors of users n_i.

Given this, every user n_i can dynamically and distributively compute the delivery probability to every other hub h_j as

$$P^d_{n_i h_j} = \max(P^t_{n_i h_j},\ \max_k (P^c_{n_i n_k}(h(n_i)) * P^t_{n_k h_j}))$$

Thus, when a user n_s wants to forward a data packet to one of the hubs h_j in the destination user's hub list, it will pick as the next hop the user

$$\{n_i \mid \max(P^d_{n_i h_j}),\ n_i \in N(n_s)\}\ \textit{iff}\ P^d_{n_i h_j} > P^d_{n_s h_j}$$

More specifically, when source has data to send, it shall forward 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 destination hub selected by the upstream user (either "most visited" or "second most visited"). 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.

4.2 Static SOLAR-KSP Algorithm

In this protocol version (referred to as **S-SOLAR-KSP**), we assume that each user knows of every other user's mobility profiles and each user distributively does the following: First, every user computes the *contact probability* with every other user. In this work, we compute these probabilities based on the simulated mobility traces, as opposed to other various ways suggested in [10, 12, 15, 19] for example. Second, we represent the contact information between all users as a complete 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 [5] to find k shortest paths (KSP) to every other destination, such that:

1. a path with the minimum total weight is chosen first
2. each path has a different next hop user from source.

Each of these KSPs then shall give the *delivery probability* for the respective pair of users via other intermediary peers.

Once these KSPs are constructed, 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 not within radio range, it caches a copy of the packet for only a predetermined time interval T, during which it may send copies of the packet to all the next hop users on the k-best paths that come within radio range. Each downstream user in the path repeats this same process as that packet gets forwarded towards the destination.

4.3 Dynamic SOLAR-KSP Algorithm

In this protocol version (referred to as **D-SOLAR-KSP**), 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 and stores them (instead of storing only up to k entries). 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 does not try to forward to any other users in the same 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.

5. PERFORMANCE RESULTS

In this section, we present the simulation results to compare the performance of the SOLAR protocols: ***S-SOLAR-KSP, D-SOLAR-KSP***, and ***SOLAR-HUB*** using the GloMoSim [25] simulator. In this paper, we have chosen k to be 2 for each of these multi-path algorithms as our other results omitted from this paper have indicated that this value of k represents a good tradeoff between performance and overhead. We also include the Epidemic Routing protocol [21] (referred to as ***EPIDEMIC*** in this paper) in our comparisons because of its simplicity and effectiveness in dealing with intermittently connected networks.

For simulation, we consider an ICMAN built within a campus consisting of several buildings (hubs) in accordance with the findings from our study [6] of an year long wireless users' mobility traces on ETH Zurich campus. In the Probablistic Orbit model simulated, the users spend most of their time within a number of hubs, and intermittently move between hubs. To model realistic speeds of mobile users within such a network, we consider the work in [13, 24] and fix the Inter-Hub and Intra-Hub time/speed parameters, along with the other simulation parameters and their default values or range of values as shown in Table 1.

We chose three metrics to evaluate the performance of each protocol: *data throughput* = (data packets delivered)/(data packets generated); *network byte overhead* = (total bytes transmitted)/(total data packets delivered); *average end-to-end data delay* = (total time taken to locate destinations and deliver all data packets)/(total data packets delivered).

In what follows, we will examine how the total number of hubs, and the total number of users affect the protocol performance. To this end, we vary one of these two factors while fixing all other parameters to their default values. Each point in the plotted results is averaged over six different simulation runs with varying random seeds.

5.1 Variation in Number of Hubs

The number of hubs in the terrain affects protocol performance due to its direct impact on the expected user density within hubs, given a fixed number of users. However, SOLAR-HUB is seen to have the maximum throughput (Figure 2(a)) at the cost of a higher overhead when compared to

Table 1: Simulation Parameters

GENERAL PARAMETERS			
Simulation Duration (each run)	3000s	Terrain Size	1000m x 1000m
Number of Users (*Users*)	*Vary*, (Default= 100)	Radio Range	125m
Cache Size	*Vary*, (Default= 200 Packets)	Cache Timeout	*Vary*, (Default= 400s)
MAC Protocol	IEEE 802.11	Mobility Model	Probabilistic Orbit
ORBIT PARAMETERS			
Number of Hubs	*Vary*, (Default= 15)	Hub Size	50m x 50m
Hub Stay Time	Exponential (Mean= 50s)	Hub List Timeout	None
Hub List Size	2 to Number of Hubs	Inter-Hub Transition Time	Exponential (Mean= 40s)
Intra-Hub Pause	1s	Intra-Hub Speed	1m/s-10m/s
TRAFFIC PARAMETERS			
CBR connections	30 (120 packets each) Random	Data Payload	1460 bytes per packet

the other SOLAR protocols (Figure 2(b)). Its consistency in performance is attributed to the assumption that each user knows of the next hub it is going to visit, which aids in the next hop selection process. In contrast, D-SOLAR-KSP closely matches the throughput of SOLAR-HUB with a overhead as low as that of S-SOLAR-KSP. D-SOLAR-KSP performs better than its static counterpart S-SOLAR-KSP mainly due to its flexibility in selecting the next hop. However, both KSP based protocols benefit from higher user density when their chances of meeting a suitable neighbor (i.e., an user from the N^{ksp}_{next} set) increases, thereby increasing delivery probability and decreasing the end-to-end delay. Hence when the number of hubs increases, the user density within hubs decreases and both of these protocols show a steady decrease in their data throughput (as seen in Figure 2(a)) and a steady increase in the end-to-end delay (as seen in Figure 2(c)). On the other hand, the non-mobility aware and purely opportunistic EPIDEMIC protocol is seen to have the lowest throughput, maximum overhead (we had to omit it from the plot in Figure 2(a) due to its huge values that were on an average 100 times worse than SOLAR-HUB) and the longest end-to-end delay when compared to all the SOLAR protocols.

5.2 Variation in Number of Users

In this section, we study the effect of varying the number of users in the network on the performance of the protocols. Given a fixed terrain size and radio transmission range, the total number of users directly impact the network connectivity. As seen from Figure 3(a), SOLAR-HUB has the maximum throughput similar to that seen before in Figure 2(a), closely followed by D-SOLAR-KSP, while S-SOLAR-KSP and EPIDEMIC have much lower throughput. Once more, as seen in Figure 3(b), SOLAR-HUB is penalized in the cost of network byte overhead, whereas D-SOLAR-KSP and S-SOLAR-KSP have much lower overhead. EPIDEMIC once again performs much worse and had to be omitted from this graph for its enormously high range of values for overhead. Figure 3(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 also studied the effect of varying hub sizes while keeping the radio range a constant, but found similar relative results for each hub size considered. We have also 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. However, it is evident from the above performance comparison that all the SOLAR variations perform much better than the conventional approach of Epidemic Routing, without having to compromise on any of data throughput, network overhead or end-to-end data delay.

6. CONCLUSION

Efficient location management and routing in mobile ad hoc networks has long been a challenging problem for researchers. Recently, a similar problem is being studied under the additional constraints of network disconnections, common within ICN. The unavailability of contemporaneous end-to-end path from a source to a destination through intermediary peers renders most reactive and proactive routing protocols useless. While the work [11] has assumed the deterministic mobility of the users, others [19, 21] have assumed total random mobility. Neither of these assumption applies to mobile users and accordingly ICMAN under the consideration. In the absence of any knowledge on the user mobility, efficient routing remains a daunting task.

In this paper, we have exploited the user's semi- deterministic movement patterns in designing efficient routing protocols for ICMAN based on users' mobility profiles. In particular, we have taken advantage of users' sociological orbital movement among a set of socially significant places (or hubs), which has been validated through the analysis of wireless users' mobility traces [6]. We have proposed three *Sociological Orbit aware Location Approximation and Routing (SOLAR)* algorithms that leverage the underlying orbital mobility information to route data within an ICMAN more efficiently than other conventional routing approaches (e.g., Epidemic Routing [21]) in an ICMAN, in terms of a higher data throughput, a lower network overhead, and a shorter end-to-end data delay.

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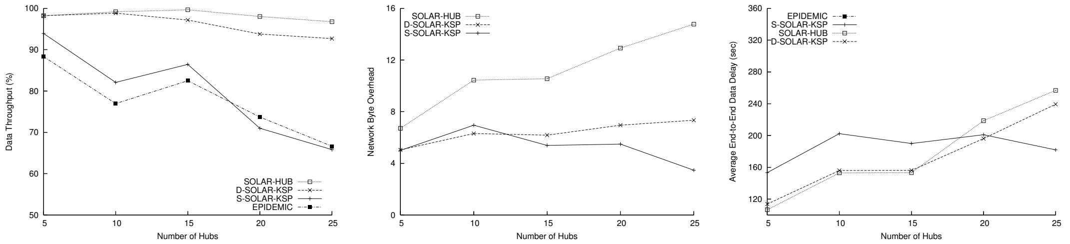
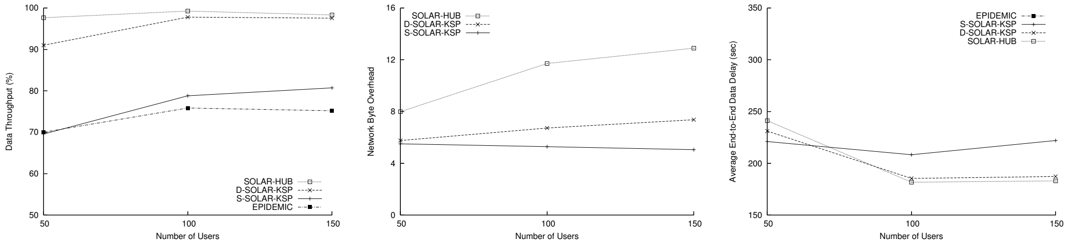


9(a) Data Throughput (%) 9(b) Network Byte Overhead 9(c) End-to-End Data Delay

Figure 2: Protocol Performance vs. Number of Hubs



9(a) Data Throughput (%) 9(b) Network Byte Overhead 9(c) End-to-End Data Delay

Figure 3: Protocol Performance vs. Number of Users

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