Participant Recruitment and Data Collection Framework for Opportunistic Sensing: A Comparative Analysis

Güliz Seray Tuncay, Giacomo Benincasa and Ahmed Helmy
Department of Computer and Information Science and Engineering
University of Florida
Gainesville, FL 32611
{gstuncay, giacomo, helmy}@cise.ufl.edu

ABSTRACT

Mobile crowdsensing is a novel approach that exploits the sensing capabilities offered by smartphones and users' mobility to sense large scale areas without requiring the deployment of sensors in-situ. Opportunistic sensing utilizes users' normal behavior to crowd-source sensing missions. In this work, we propose a novel framework for fully distributed, opportunistic sensing that coherently integrates two main components that operate in DTN mode: i. participant recruitment and ii. data collection. We adopt a new approach to match mobility profiles of users to the coverage of the sensing mission. We analyze several distributed approaches for both components through extensive trace-based simulations, including epidemic routing, PROPHET, spray and wait, profile-cast, and opportunistic geocast. The performances of these protocols are compared using realistic mobility traces from wireless LANs, various mission coverage patterns and sink mobility profiles. Our results show how the performances of the considered protocols vary, depending on the particular scenario, and suggest guidelines for future development of distributed opportunistic sensing systems.

Categories and Subject Descriptors

C.2.4 [**Computer-Communication Networks**]: Distributed Systems—*distributed applications*; C.2.2 [**Network Protocols**]: Routing Protocols

Keywords

Crowdsensing, DTN, Mobile Computing, Opportunistic Sensing

1. INTRODUCTION

Recent advances in sensing capabilities, storage capacity, and computation power of smartphones–along with the increasing pervasiveness of their adoption–led to the development of crowdsensing applications that exploit the capabilities of these devices to crowdsource data collection about the users' surroundings. Mobile crowdsensing has therefore become a viable approach for large-scale urban sensing activities that do not require the deployment of sensors in-situ. Lane et al. discern two classes of people- centric sensing activities: participatory and opportunistic sensing [1]. Participatory sensing requires the participants to *consciously opt to meet the application requests* [1]; therefore, it is necessary that the participants are engaged in the sensing activity, or that the participants are rewarded to achieve better involvement. Conversely, in opportunistic sensing, minimal or no interaction with the participants is required; in fact, opportunistic sensing applications may run in the background and opportunistically collect data with no need to interact with the participant. For example, an application as the one described in [2], that passively monitors 2G/3G data to assess the quality of mobile Internet from end-terminals, may benefit from the adoption of a distributed data collection model. The users would not need to upload their measurements using the cellular network, therefore saving bandwidth. High participation is crucial for the success of crowdsensing activities. Because of the low degree of interaction that the user is required to provide, opportunistic sensing may be a suitable and inexpensive way to achieve high participation; however, current approaches for crowdsensing rely on centralized registries to recruit possible participants [3]. Moreover, the collected data is uploaded from the participants to remote servers by using cellular networks. These approaches may lead to privacy and economical concerns that may work as a disincentive for participation. It is therefore critical to devise alternative approaches to opportunistic sensing that are autonomous and fully distributed, and therefore potentially more privacy-preserving. We propose a generic mechanism to perform the *recruitment* and *data collection* activities in a completely distributed fashion. By doing so, we recognize that many different implementations may be applied, and therefore we also recognize the need for a framework to systematically evaluate these implementations. Our major contributions are summarized as follows:

- We introduce a unified distributed recruitment and data collection framework for opportunistic sensing.
- A systematic comparative analysis is conducted for several DTN routing protocols for the considered approaches. A rich set of test suites and scenarios are used based on real wireless traces, to assess the quality of the compared methods and identify their strengths and shortcomings.
- The findings indicate guidelines for the use of DTN routing for opportunistic sensing based on sensing mission requirements and the sink model.

CHANTS'13, September 30, 2013, Miami, Florida, USA
Copyright 2013 ACM 978-1-4503-2363-5/13/09 ...$15.00.
http://dx.doi.org/10.1145/2505494.2505502 .

The rest of this paper is organized as follows. Section II presents the related work. Section III gives background information on the used protocols, describes the overall framework and gives detailed information on how recruitment and data collection may be handled in the framework. Section IV presents a thorough evaluation and comparison of several recruitment and data collection methods. Finally, section V concludes and discusses future directions.

2. RELATED WORK

Opportunistic sensing is closely related to several other broad areas of investigation, such as participatory sensing, delay tolerant networks (DTNs), and wireless sensor networks (WSNs). In particular, the recruitment problem has been discussed in the literature on participatory sensing, and more in general, on crowdsourcing. The problem of data collection has been throughly studied in the areas of WSNs. Finally, a wide array of related literature can be found in the area of DTNs.

A recruitment service seeks individuals that are able and willing to collect data about a particular phenomenon, and selects the subset that matches a set of required campaign specifications. Reddy et al. [3] propose a comprehensive, recruiting framework that allows the selection of participants based on specific campaign specifications that take into account the participants' reputation and their geographical and temporal coverage, in other words their availability to collect data in a defined geographical area at a defined time. Such information can be retrieved from personal data vaults. The access and the granularity of the results obtained by querying these data vaults are controlled by participant-defined policies. While the profile information can be collected by the users in a distributed fashion, the profiles need either to be stored in centralized repositories or it is necessary to build a centralized registry containing the identities that can then be contacted to retrieve their profile information. Both approaches can be easily automated; however, they rely on a centralized system. In our previous work [4], we suggested that profile-cast [5] may be used to collect profile information in a distributed and anonymous fashion.

Data collection is a problem that has been widely studied in the context of WSNs, and numerous techniques have been devised to efficiently collect, gather and elaborate data in these often resource constrained environments. However, the majority of the literature concerning data collection in WSNs does not take mobility into account, or relies on the assumption that either the sinks or the sensor nodes are static [6], or relies on the possibility to control the trajectory of the sinks [7]. Because of the unknown position of the sinks due to their mobility, and due to the continuous change of the topology, the problem of routing the sensor data to the sinks is analogous to the routing problem in DTNs. Epidemic routing [8] performs a sort of flooding and it was the first seminal approach to routing in DTNs. Several approaches [9, 10, 11] have been proposed to optimize the efficiency of flooding-based routing. In [9], a gossip-based probabilistic approach to information dissemination in DTNs is presented. This simple approach outperforms regular gossip in terms of delivery ratio when the network is dense; but it is beaten when the network is sparse. Moreover, purely-probabilistic approach could not take advantage of the possible periodicity of the nodes' trajectories. We will discuss [10, 11] in more detail in Section III. In [12], Mascolo et al. propose a context-aware adaptive routing protocol that attempts to exploit the encounter history of the nodes, their movement and their availability of resource, in order to select message carriers that have a higher probability to deliver their messages. This approach shows good performance in a constrained environment; however, because of its reliance on encounter history, it may not perform efficiently in highly dynamic environments, where the likelihood of two nodes to encounter multiple times is limited due to continuous churning. The specific problem of data collection in highly mobile sensor networks has been studied in [13], where the protocol uses an estimate of the mobility level of the nodes instead of encounter histories to to estimate the delivery probabilities. In the particular scenario of opportunistic sensing, the level of mobility may be a better indicator of the likelihood of a node to meet with a sink; however, when the area of deployment of the sink is known a-priori, considering only the mobility level of a node may lead to suboptimal performances. A better approach would exploit the likelihood of a node to visit the locations where the sink is deployed. Alternatively, location-based approaches that use historical information on the visited locations, but that employ different metrics, can be considered. For instance, in [14] the authors propose an opportunistic geocasting algorithm that implements a gradient-based routing protocol that forwards the messages based on the expected visiting rate of the destination region of the message.

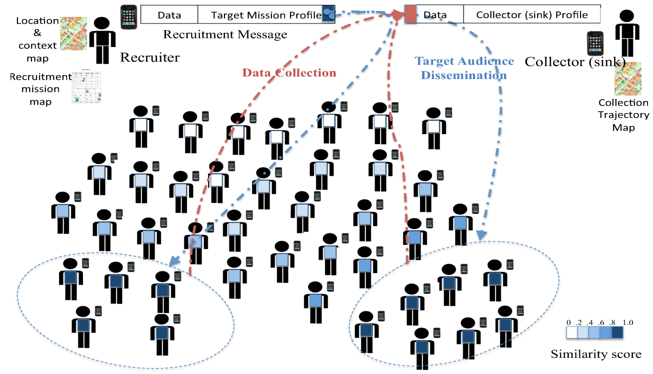

Figure 1: Overview of recruitment and data collection. Recruiter has a recruitment map that specifies the target locations. Destination is defined by the target interest profiles or solely by target locations. Destination(s) will match based on a similarity score. Such score can be inferred based on behavioral aspects of the user. The match could lead to one (or more) groups satisfying the similarity score. Participants send their collected data to the sink's profile or directly to the sink's id.

3. THE OVERALL FRAMEWORK

Opportunistic sensing activities consist of two phases: *recruitment* and *data collection*. The aim of the *recruitment* phase is to notify an upcoming sensing activity to the nodes that are likely to be able to take part in it. We call this set of nodes *candidate sensing nodes*. Since our focus is opportunistic sensing, where the users are not expected to change their behavior to take part in the sensing activity, some candidate sensing nodes may choose not to participate in the activity. We call the set of nodes that participate in the sensing activity, *sensing nodes*. The aim of the *data collec-*

tion phase is to return the sensory data that was collected by the sensing nodes to the organizer of the sensing activity. Figure 1 illustrates the components of the recruitment and data collection activities.

In order to perform distributed recruitment, we propose the use of one or more *recruiter nodes* that advertise the sensing activity, while sensor data will be delivered to a set of *sink nodes*. The protocols used to reach the candidate sensing nodes and the sink are inherently different and will be explained in the next section.

Our framework coherently integrates participant recruitment and data collection components and measures the performances of the routing protocols that are suitable in the context of opportunistic sensing for infrastuctureless environments. In order to evaluate these performances, we designed a set of trace-driven simulation scenarios. We compared the results based on many criteria, including the number of reached candidate sensing nodes (only for recruitment), overhead ratio, delivery probability and latency.

3.1 Scenarios

Recruiter nodes can either be selected from the pool of users, or can be deployed specifically for the sensing activity prior to its start. Other important factors to consider are the mobility of the recruiter nodes, the location(s) that they visit, and the duration of their deployment.

In the scenarios that we designed, we focused on the case of specifically-deployed recruiter nodes. Because of the critical impact of mobility on the dissemination performance [15], we included both mobile and static sink cases in our simulations:

- Mobile recruiter node: In this scenario, the recruiting node is mobile and travels between all the sensing locations.
- Static recruiter node: In this scenario, the recruiting node is static and deployed only in one of the sensing locations.

We propose the use of specifically-designated sinks for the collection of user data and suggest that the participating nodes opportunistically exploit ad hoc encounters to reach data sinks. Analogously to the recruitment activity, data sink nodes for the collection of user data may either be temporarily deployed for the sensing activity, or selected from the pool of users. In our work we focus on the former case. For the evaluation of data collection, we used the following scenarios:

- Mobile sink for data collection: The sink is mobile and travels all the sensing location in order to collect data.
- Static sink in the sensed area: In this scenario, the sink is deployed only in one of the sensing locations.
- Static sink outside of the sensed area: In this scenario, the sink is deployed only in one of the sensing locations.

The number of the designated data sinks and recruiter nodes is expected to be orders of magnitude less than the number of sensing nodes.

3.2 Routing Protocols

The recruitment and data collection activities are intrinsically different: recruiter nodes need to disseminate a small recruiting message in order to reach a large set of candidate sensing nodes. Conversely, sensing nodes need to send a potentially large amount of data to a limited number of sink nodes. Hence, the set of protocols that can be adopted for the two activities are different.

3.2.1 Protocols for recruitment

Profile-cast [5] is a behavior-oriented protocol for DTNs that aims to send messages to the nodes matching a certain target *behavioral profile*, rather than explicit IDs. Each node can autonomously construct its profile by monitoring the places it visits and the time spent at those locations. Based on this information, the node can build an association matrix that represents the percentage of time the node spent at various locations. Several metrics can be used to calculate the similarity between two profiles. In [5], the authors follow a singular value decomposition based metric for this purpose. Information is routed in two phases: *gradient ascend* and *group spread*. During the gradient ascend phase, messages are diffused following an ascending gradient of similarity between the behavioral profile of the node and the target profile. No replication is allowed in this phase. When the message reaches a node with a higher similarity to the target profile than a certain threshold th_{sim}, the protocol switches to group spread mode. Group spread mode allows replication, and messages are copied from the holder to an encountered node with a higher similarity than th_{sim}. This double-phase of operation allows profile-cast to achieve a fair trade-off between overhead and delivery ratio. Profile-cast is a suitable protocol for recruitment since it relies on stable user behavior that is based on mobility history information; thus, it enables us to recruit only the nodes that are likely to be in the sensing area when the sensing activity is taking place.

Opportunistic geocast [14] takes a different approach than profile-cast. It is a mobility-history based geocasting technique that makes routing decisions based on the expected visiting rate (EVR) of users to the destination region. Opportunistic geocast was designed to work in DTNs, and does not rely on the assumption of continuous network connectivity, as opposed to most previous approaches to geocasting. The EVR metric is used for choosing better forwarders to the destination region. The message follows an ascending gradient of EVR until it reaches the destination region. A local broadcast is carried out afterwards to reach all the nodes in the same region. As it can be seen, this protocol works in a similar way to profile-cast in the sense that it first performs a gradient-based routing to the intended group of users; then, a controlled broadcast is performed to reach all the members of the intended audience. The difference is in the metric used for selecting the forwarders.

3.2.2 Protocols for data collection

In **epidemic routing** [8], nodes continuously replicate and transfer messages to newly-encountered nodes that do not already possess a copy of the message. This results in a high delivery rate and low latency as well as high overhead due to its flooding based nature. This protocol will be used as a base-line in the performance comparisons.

Prophet [11] is a DTN routing protocol in which the forwarding decision is made based on delivery probability to the destined node. This probability is computed based on node encounter statistics. When two nodes encounter, the message carrier forwards the message to the encountered node if the delivery probability of the message is higher at the other node. Prophet has a more selective forwarding mechanism than epidemic routing, that is why, it results in a lower overhead.

Spray and wait [10] is a DTN routing protocol that significantly reduces overhead of flooding-based protocols by spraying only a limited number of copies of the message to the network. When enough copies are spread, the protocol switches to direct transmission mode. This results in a good trade-off between single-copy and multi-copy protocols in terms of delivery rate, latency and overhead.

We also use modified versions of profile-cast and opportunistic geocast for data collection. We will talk about these modifications in the next section.

3.3 Implementation Details

The chosen protocols may need to be modified accordingly to suit the need of these activities. In this section, we describe the modifications that we applied to these protocols.

3.3.1 Recruitment

Profile-cast can be used to perform the dissemination, and a profile which includes the locations in the sensing area can be used as the target profile. However, unlike the original version of profile-cast, where the aim is to reach nodes matching a certain target profile, for recruitment it is necessary to also reach the nodes that match only a *part* of the target profile. In other words, if the sensing area is large and consists of multiple locations, nodes that visit only a subset of the sensing locations are still able to contribute to the sensing activity, thus should also be recruited. It is therefore necessary to change the similarity metric to be able to evaluate the similarity between a subset of the locations and the behavioral profile of the nodes. Upon an encounter with a message holder, the encountered node's profile will be compared to the sets in the power set of the actual target profile and the message will be forwarded if for any of these sets the similarity is above the similarity threshold.

In opportunistic geocast, the expected visiting rate (EVR) is calculated for hexagonal cells that make up the entire routing space for a given geographical region. We modified this metric in such a way that EVR will be calculated for the buildings in the traces, not for the hexagonal cells. The reason for this modification is that we do not have a more accurate location information for the users. We also devised a geographical dissemination protocol, **geo-dissemination**, which works in a similar way to opportunistic geocast, but is different in the sense that a node is allowed to keep a copy of the message and forward it several times.

3.3.2 Data Collection

When the locations visited by the sink are known a-priori, profile-cast and geocasting may also be used for the purpose of data collection; This location information can be used to describe the behaviour of the sinks, and therefore included in the recruitment message, and the used by the sensing nodes as a target profile for the data messages. Analogously to the recruitment case, data collection aims to reach *any* of the nodes that match the target profile. Because the sensing nodes are expected to greatly outnumber the number of data sinks and that they may produce a large number of messages, it is critical to limit the data replication by having the nodes run solely in gradient ascend mode. While this may significantly increase the delivery time, in many sensing applications it is not the case.

Opportunistic geocast can also be applied when the locations visited by the sink(s) are known. However, due to the fact that broadcasting of collected data will result in a high communication overhead, this phase can be omitted and only the geographical routing phase (ascending gradient phase) in the protocol can be applied to reach the sink(s).

When the sink locations are unknown, regular DTN routing protocols may be used, if the sink IDs are known. We did not modify epidemic routing, prophet or spray and wait for this purpose.

4. EVALUATION AND RESULTS

In order to evaluate our approach, we developed a trace-driven simulation in a way analogous to what is described in [5, 16]: we use the extensive WLAN traces that were collected on the USC campus in 2006 [17] and we assume users to be in communication range when they are associated with the same access point at the same time. Because of the limited use of smartphones at the time, most of the users in these traces access the network using their laptops, and therefore, as also pointed out in [16], their mobility is restricted. While traces that record the mobility of the users by instrumenting more portable devices, such as cellular phones or sensors, are available, they tend to be much smaller in size than the WLAN traces. While currently available cellular phone or sensor traces collect information for hundreds of nodes, at most, the WLAN traces that we used, collect over 4000 users' traffic from 72 buildings.

For the opportunistic sensing activity, we designed a test scenario in which the sensing activity is scheduled on a part of the USC campus. Since opportunistic sensing works best when there is high participation in the sensing activity, the sensing activity was scheduled to take place in the area including the seven most visited locations. A single node, designated both as recruiter and data sink, is deployed one week before the start of the sensing activity, and is either fixed or continuously moves along a seven waypoint predefined path. The path of the sink is assumed to be included in the recruitment message and this behavior is continuously repeated along the duration of the sensing (from 8am to 8pm).

4.1 Recruitment

In our recruitment scenario, the recruiter node is configured to send a recruitment message every hour until the start of the sensing activity. We analyzed the traces and learned that the number of nodes that appear in the sensing area during the sensing activity, and hence should be recruited, is 163.

4.1.1 Mobile sink for recruitment

In this scenario, the recruiter is mobile and travels between the top seven most visited locations. We compare the performances of profile-cast, opportunistic geocast and geo-dissemination for this scenario. While the size of the recruitment message may be negligible, we are still interested in limiting the number of unsolicited messages received by users that will not be able to participate in the sensing activity. Figure 2 shows the number of nodes that received at least one recruitment message at a specific time for each of these protocols, and the number of these nodes that will be

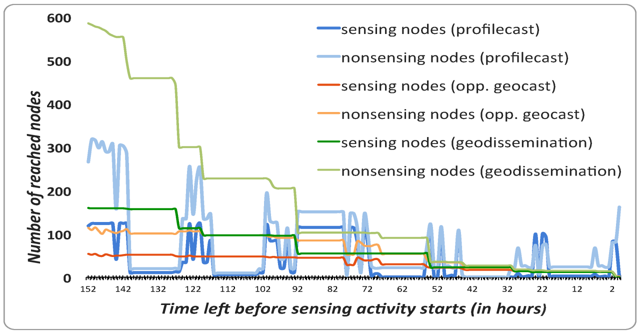

Figure 2: Number of nodes that received the recruitment message (recruited and not recruited) versus time.

able to take part in the sensing activity. We summarize the comparison as follows:

1. Opportunistic geocast with $\lambda = 1.65 \times 10^6$ recruits the smallest number of nodes with the smallest overhead. 78 nodes are recruited in total. $\lambda = 1.65 \times 10^6$ is the EVR for a node that visits the destination once a week.
2. 159 nodes are recruited with geo-dissemination with $\lambda = 1.65 \times 10^6$. However, the overhead is also the highest due to its flooding-based nature. The number of reached non-sensing nodes is almost two times greater than that of profile-cast.
3. 126 nodes are recruited with profile-cast with a moderate overhead. The overhead is also less compared to geo-dissemination since flooding is avoided in the protocol.

4.1.2 Static sink for recruitment

In this scenario, the sink is fixed at one of the nine locations (seven target, two non-target locations) for the duration of the recruitment, and stays there until the end of data collection. Figure 3 shows the number of reached nodes by profile-cast, opportunistic geocast and geo-dissemination when the sink is fixed at a given location. Our results can be summarized as follows:

1. In case of an immobile sink, the number of nodes reached by opportunistic geocast decreases significantly. This shows that mobility has a considerable effect on the performance of this protocol.
2. Profile-cast reaches almost the same number of nodes as in the mobile case, with the exception of locations JKP and RGL. By analyzing the traces, we found out that the number of encounters that take place at JKP and RGL during the sensing time is very limited, and this degrades the performance.
3. Geo-dissemination reaches almost the same number of nodes as in the mobile sink case due to its multi-copy nature.

The overhead ratios of the protocols are similar to those in the mobile sink case. When the sink is mobile, profile-cast offers the best trade-off between the number of reached sensing nodes and reached non-sensing nodes since its overhead is considerably less than that of geodissemination and it reaches a satisfactory number of nodes. For when the sink is static, profile-cast is still a valid option since the results are similar. On the other hand, when the network is sparse,

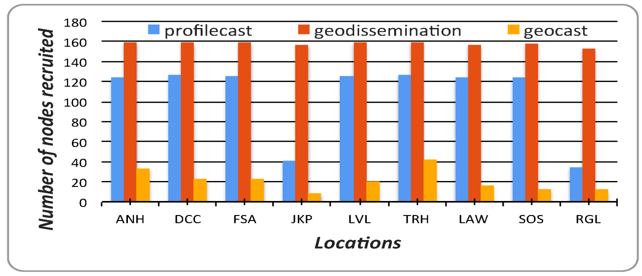

Figure 3: Number of recruited nodes for each static sink location. All locations except SOS and RGL are target locations from which users are recruited.

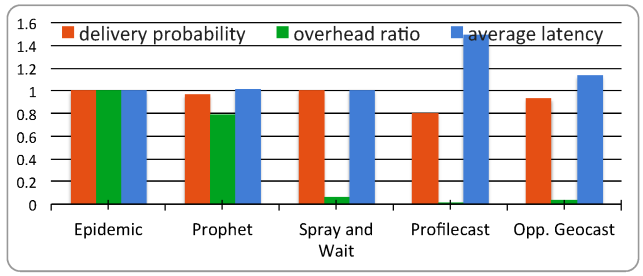

Figure 4: Data collection performance comparison for mobile sink (normalized w.r.t epidemic routing)

geo-dissemination may provide better performance, in terms of recruited sensing nodes.

4.2 Data Collection

For the evaluation of our data collection method, we assume ideal recruitment, meaning that all the nodes that are in the sensing area are recruited and take part in the sensing activity. The sensing nodes are assumed to send their collected data to the sink hourly.

We use the ONE simulator [18] to compare the performances of profile-cast, PROPHET, epidemic routing, spray and wait and opportunistic geocast DTN routing protocols. We focus on three major performance measures: 1) delivery ratio, 2) average delivery time and 3) overhead ratio.

4.2.1 Mobile sink for data collection

Figure 4 depicts the normalized performance metrics with respect to those of epidemic routing and shows the following results:

1. Epidemic routing leads to the highest delivery ratio and the minimum latency due to its aggressiveness; however, it also has the highest overhead ratio.
2. Prophet leads to a high delivery ratio, relatively low latency and a lower overhead ratio compared to epidemic routing. However, PROPHET's overhead ratio is still high because of its multi-copy nature. Because of its high overhead ratio, PROPHET may not be applicable when the use of network resources is a great concern.
3. Spray and wait leads to a delivery ratio as high as that of epidemic routing, an overhead ratio that is significantly lower than all protocols except profile-cast and opportunistic geocast, but it beats these two protocols in terms of latency. In our experiments, we set the initial number of copies to six.

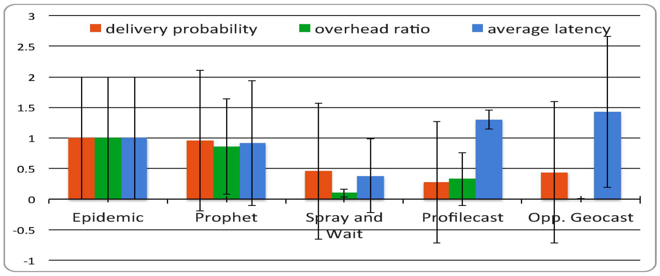

Figure 5: Performance comparison of different data collection methods for static sink (normalized w.r.t epidemic routing)

4. Opportunistic geocast has a low overhead and a high delivery ratio. In terms of latency, it performs worse than other protocols except profile-cast.
5. Profile-cast (in gradient ascend mode) leads to a high delivery ratio and the lowest overhead ratio among other protocols due to its single-copy nature. It is desirable to use in opportunistic sensing scenarios which can handle only a low load on the network resources.

It is worth noting that we allow PROPHET to collect encounter statistics only after the sensing starts. The rationale behind this is that we want to limit the amount of exchange of sensitive information.

4.2.2 Static sink for data collection

In this scenario, the sink is fixed at one of the nine locations (seven target, 2 non-target locations), and collects data from all the eligible sensing nodes that are present in any of the seven target locations. Figure 5 shows the average performances of all the nine locations. The results are normalized with respect to those of epidemic routing. The performances of all protocols drop significantly for this scenario. The absolute delivery ratio is consistently below 50% for all protocols. The reason for this inefficiency is that the probability of encountering the drops drastically, and messages need to follow a longer route, which do not always exist. In particular spray and wait's performance drops more significantly than that of other protocols. The reason for this drastic performance drop is that spray and wait blindly replicates the messages to a limited number of nodes, without trying to select better forwarders that are more likely to encounter the sink. It can be seen from Figure 5 that PROPHET has the most consistent results with the mobile sink case; it is interesting to observe that although PROPHET starts collecting encounter information only after the start of the sensing activity, it still achieves a high delivery ratio. However, a two-week deployment for the sink may not always be possible. Prophet's performance may degrade if the deployment time of the sink is reduced.

5. CONCLUSION AND FUTURE WORK

In this work, we proposed a framework for autonomous and distributed recruitment and data collection in opportunistic sensing. We investigated the feasibility of several applicable state-of-the-art DTN routing protocols for both the recruitment and data collection components, and provided a comprehensive analysis of their performances. Our results show that profile-cast is a reliable protocol for participant recruitment due to its comparably lower overhead and higher delivery rate. For the case of data collection, spray and wait outperforms the other protocols for the mobile sink case, although we showed that its performance degrades significantly when the sink only visits a subset of the sensed area, or does not visit the sensed area at all, and therefore there are only few, or no, direct encounters between the sensing nodes and the sink.

As a part of our future work, we plan to investigate the addition of the progress review phase [3] into the framework and introduce online recruitment for selecting additional participants while the sensing is already taking place for participant recruitment. Additionally, we plan to consider recruiting sinks from the pool of users based on their mobility histories, by taking into account metrics such as behavior stability and variety of encounters.

References

[1] N. D. Lane, S. B. Eisenman, M. Musolesi, E. Miluzzo, and A. T. Campbell. Urban sensing systems: opportunistic or participatory? In *Proc. HotMobile*, 2008.

[2] G. Hourton, G. Del Canto, J. Bustos, and F. Lalanne. Crowd-measuring: Assessing the quality of mobile internet from end-terminals. In *NetGCooP*, 2012.

[3] S. Reddy, D. Estrin, and M. Srivastava. Recruitment Framework for Participatory Sensing Data Collections. In *International Conference on Pervasive Computing*, 2010.

[4] G. S. Tuncay, G. Benincasa, and A. Helmy. Autonomous and distributed recruitment and data collection framework for opportunistic sensing. *SIGMOBILE Mob. Comput. Commun. Rev.*, 2013.

[5] W. Hsu, D. Dutta, and A. Helmy. CSI: A paradigm for behavior-oriented profile-cast services in mobile networks. *Ad Hoc Networks*, 2011.

[6] E. B. Hamida and G. Chelius. A Line-Based Data Dissemination Protocol for Wireless Sensor Networks with Mobile Sink. In *IEEE International Conference on Communications*, 2008.

[7] S. Basagni, A. Carosi, E. Melachrinoudis, C. Petrioli, and Z. M. Wang. Controlled sink mobility for prolonging wireless sensor networks lifetime. *Wireless Networks*, 2007.

[8] A. Vahdat and D. Becker. Epidemic routing for partially-connected ad hoc networks. Technical report, Duke University, 2000.

[9] Y. Wang and H. Wu. Delay/fault-tolerant mobile sensor network (dft-msn): A new paradigm for pervasive information gathering. *Mobile Computing, IEEE Transactions on*, 2007.

[10] T. Spyropoulos, K. Psounis, and C. S. Raghavendra. Spray and wait: an efficient routing scheme for intermittently connected mobile networks. In *Proc. WDTN*, 2005.

[11] A. Lindgren, A. Doria, and O. Schelén. Probabilistic routing in intermittently connected networks. *SIGMOBILE Mob. Comput. Commun. Rev.*, 2003.

[12] C. Mascolo and M. Musolesi. Scar: context-aware adaptive routing in delay tolerant mobile sensor networks. In *Proc. IWCMC*, 2006.

[13] A. Kinalis and S. Nikoletseas. Adaptive redundancy for data propagation exploiting dynamic sensory mobility. In *Proc. MSWiM*, 2008.

[14] Y. Ma and A. Jamalipour. Opportunistic geocast in disruption-tolerant networks. In *IEEE GLOBECOM*, 2011.

[15] F. Bai, N. Sadagopan, and A. Helmy. Important: a framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks. In *INFOCOM*, 2003.

[16] W. Hsu, D. Dutta, and A. Helmy. Structural Analysis of User Association Patterns in University Campus Wireless LANs. *IEEE Transactions on Mobile Computing*, 2012.

[17] Mobilib: Community-wide library of mobility and wireless networks measurements. http://nile.cise.ufl.edu/mobilib.

[18] A. Keränen, J. Ott, and T. Kärkkäinen. The ONE Simulator for DTN Protocol Evaluation. In *Proc. SIMUTools*, 2009.