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Evaluation of Opportunistic Routing Algorithms on Opportunistic Mobile Sensor Networks with Infrastructure Assistance

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***Abstract*—Recently the increasing number of sensors integrated in smartphones, especially the iPhone and Android phones, has motivated the development of routing algorithms for Opportunistic Mobile Sensor Networks (OppMSNs). Although there are many existing opportunistic routing algorithms, researchers still have an ambiguous understanding of how these schemes perform on OppMSNs with heterogeneous architecture, which comprises various kinds of devices. In this work, we investigate the performance of well-known routing algorithms in realistic scenarios. To this end, we propose a heterogeneous architecture including fixed infrastructure, mobile infrastructure, and mobile phones. The proposed architecture focuses on how to utilize the available, low cost short-range radios of mobile phones for data gathering and dissemination. We also propose new realistic mobility models and metrics. Selected routing protocols are simulated and evaluated with the proposed heterogeneous architecture, mobility models, and transmission interfaces under various constraints, such as limited buffer size and time-to-live (TTL). Results show that some protocols suffer long TTL, while others suffer short TTL. We further study the benefit of fixed infrastructure in network performance, and learn that most of the opportunistic routing algorithms cannot benefit from the advantage of fixed infrastructure since they are designed for mobile nodes. Finally, we show that heterogeneous architecture need heterogeneous routing algorithms, such as a combination of Epidemic, Spray and Wait, and context-based algorithms.**

Keywords-opportunistic sensor network; opportunistic routing; heterogeneous architecture; mobility model; smartphone.

I. Introduction

Mobile phones play an important role in sensor network applications during last few years. Measurements can be gathered with either user participatory, opportunity, or both. No matter by which, data gathering is particularly meaningful when performed by many phones simultaneously. To enhance data reliability and dissemination performances, heterogeneous architecture that consists of various kinds of sensor devices is necessary. In fact, this paper is an extension of Le et al. [1] to continue with evaluation of existing opportunistic routing algorithms on heterogeneous architecture .

Sensor networks, a large collection of nodes to collect the world's physical nature, have gone through various evolution phases as depicted in Figure 1. In Wired Sensor Networks, the deployment of sufficient sensors is often bounded by the cost of wiring. Later, Wireless Sensor Networks (WSNs) have been taken into consideration to replace the existing Wired Sensor Networks, since WSNs provide a wide range of context-awareness for real-time applications at low cost. A variety of sensor types with dense deployment forms a connected wireless mesh network via low power, short-range radios, collaborating to acquire and transmit the target data to sink nodes [2]. However, limited to unchangeable topology, WSNs cannot be applied for a variety of applications with different types of architecture or inaccessible areas. Therefore, Mobile Sensor Networks (MSNs) have been presented to facilitate the data collection of sensors. But still, the cost of deploying all kinds of such required sensors is considerably high in terms of time and money.

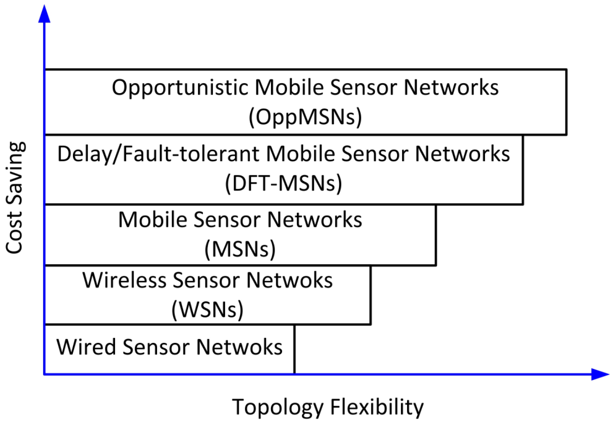

Figure 1. Evolution of sensor networks.

The next step in sensor networks is to enhance, or even replace, mobile nodes in MSNs with mobile phones. Thanks to developments in sensor technology, smart phones, such as the iPhone and Android-based phones, are equipped with a large number of sensors, including GPS, accelerometers, gyroscopes, proximity sensors and cameras. Even regular phones also have sensors: microphones, light sensors, and onboard radios. Not all mobile phones can access 3G mobile internet, especially when a disaster happens, for example, an earthquake or tsunami. But still mobile phones have the means to participate in the sensor network. This revolution is termed as Delay/Fault-tolerant Mobile Sensor Networks (DTF-MSNs) [3]. Nevertheless, the architecture of DTF-MSNs lacks infrastructure, which most real-world applications often have. To this end, we propose new type of sensor networks, of which architecture consists of fixed infrastructure, mobile infrastructures, and mobile nodes (mainly smart phones). We term the new sensor networks as Opportunistic Mobile Sensor Networks (OppMSNs). Unlike Ad-hoc Networks (VANETs) use only RSUs, OppMSNs utilize a wide range of available devices to measure and disseminate data for specific tasks. For example, through WiFi or Bluetooth radio, mobile nodes can collaborate with nearby ones, cars, buses, laptops, and the existing infrastructure-based sensor networks for data gathering.

In addition, as requiring a contemporaneous end-to-end connectivity, traditional routing algorithms such as Ad-hoc On-Demand Distance Vector (AODV) [4] or Dynamic Source Routing (DSR) [5], which can be used for MSNs, may perform poorly in scenarios where the communication paths are disrupted because of the sparse and mobility of sensor nodes. Opportunistic routing algorithms with the store-carry-forward paradigm, which can be applied for OppMSNs, have been proposed in a number of recent studies to evaluate the performance of routing algorithms on data gathering [6]–[19]. However, these algorithms use either basic scenarios or simple simulation architectures that are still quite far from real-world applications.

This paper investigates the performance of existing opportunistic routing algorithms for OppMSNs by proposing heterogeneous architecture, mobility models and metrics. The architecture includes most of real-world sensor nodes such as Road Side Units (RSUs), buses, cars and pedestrians with unpredictable movement. To achieve a realistic setting, the architecture is mapped on a real city, the city of Enschede, The Netherlands. Buffer size and time-to-live of messages are limited. We also consider heterogeneous means of communication, especially WiFi and Bluetooth. In addition, two new models, together with available ones in The ONE simulator [20], will be implemented to make the investigation more realistic. By means of simulations, the proposed architecture and models are used for the comparison of a set of opportunistic routing protocols.

The paper has the following structure: related work is discussed in Section II. Section III presents the architecture, new mobility models and evaluation metrics. The simulations and an analysis of simulation results are the subject of Section IV, which covers evaluations of movement model, algorithms' performance, and RSUs' assistance. Based on the results, Section V gives possible directions for current and future research.

II. Related Work

In this paper, we evaluate performance in term of message delivery of most well-known opportunistic routing algorithms with OppWSNs that are essentially composed of the existing wireless ad-hoc sensor networks (RSUs) and the mobile sensor networks (flocks of mobile phones). The network can be characterized as intermittent connection and sparse mobility. Conventional routing protocols [4], [5] require contemporaneous end-to-end connectivity for a data packet to be delivered. In other words, if the destination is not available on the connected path, the packet delivery will fail and no further effort is taken to secure future transmission of the data. Consequently, routing protocols must be adapted for these new types of networks. Numerous opportunistic routing algorithms have been proposed in the last few years with different mechanisms [3], [6]–[15], [17]–[19], which can be generally categorized based on either the type of network (*without infrastructure* and *with infrastructure*) or the pre-known information of the networks (*Stochastic* and *Context-based*) as defined in [21]. These categorizations slightly overlap as depicted in Figure 2. If networks are sparse and most nodes possess unpredictable movement, the stochastic protocols are more appropriate. In our opinion, an algorithm that can combine advantages of stochastic and context-based approaches is most suitable for our considered networks since the global knowledge of fixed and mobile infrastructures perhaps improves the routing performance of mobile nodes, which have unpredictable movement.

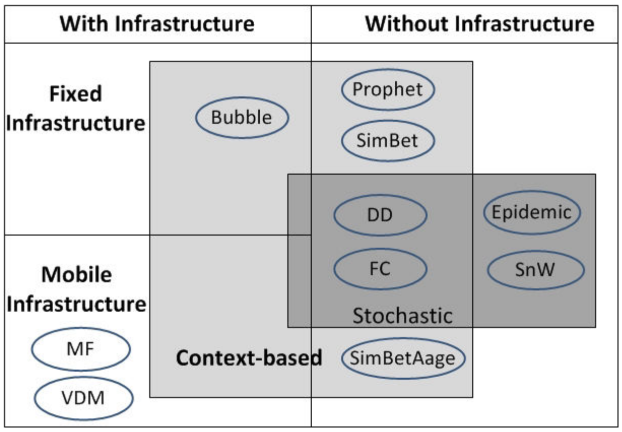

Figure 2. Categorizations of routing protocols in opportunistic networks.

A. Routing Without Infrastructure Assistance

Stochastic routing protocols deliver messages by simply disseminating them all over the network. Being passed from node to node, messages will be gradually delivered at the destination. Epidemic Routing [12] diffuses messages similar to the way virus/bacteria spread in biology. When encountering others, a node will replicate and broadcast the messages to them. These nodes that just received the messages will move to other places and continuously replicate and transmit messages to other nodes whenever they are in range of communication. Though increasing the possibility of message delivery, the method results in flooding the network and rapidly exhausting available resources. Direct Delivery (DD) [13] only delivers the holding messages directly to the destination; therefore, DD saves huge amounts of resources but decreases significantly the delivery probability. Spray and Wait (SnW) [14] is a tradeoff between multi-copy scheme (Epidemic) and single-copy scheme (Direct Delivery) by finding an optimal number of message copies and dividing the message delivery process into two phases (*spray phase* and *wait phase*). First Contact (FC) [15] is a variant of single-copy scheme, which sends messages to the first encountered node or a random node if there are more than one.

In general, context-based protocols use information of historical contacts. Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) [16] is a well-known Context-based routing protocol based on encounter. PRoPHET estimates the delivery predictability for each known destination at each node before passing a message. The estimation relies on the history of encounters between nodes. SimBet [17] uses historical contacts to calculate two metrics, similarity and betweenness. The similarity, which is calculated by how frequently a node and its destination have met, is meant of how socially connected such two nodes are. Meanwhile, the betweenness, which is calculated by how many nodes which a node has met, is meant of how interconnected a node is. However, if the utility metrics are equal, SimBet will prevent its forwarding behavior. To improve this flaw, BUBBLE [18] adds the knowledge of community structure to ensure message diffusion. Since the social knowledge varies over time, information used BUBBLE may be outdated. In addition, the betweenness may be useless if the message is near its destination. Motivated by this shortcoming, SimBetAge [19] is proposed.

B. Routing With Infrastructure Assistance

Data Mule [22] is designed to exchange messages between the close fixed infrastructure via mobile nodes with random movement. Conversely, Virtual Data Mule (VDM) [11], Message Ferrying (MF) and its variants [10], [23], [24] try to improve network performance by increasing the encounter probability via predefined movement. The ferries shuttle along the predefined routes in the dedicated region. Meanwhile, mobile nodes have tendency to move towards ferries to send messages. Such assumption makes the algorithms limited in specific scenarios with the majority are buses and bus travelers. In fact, these algorithms are entirely constrained by the route and time schedule of ferries. Without the route information, the algorithms will perform poorly.

C. Routing for OppMSNs

To our best knowledge, little attention has been given on how to apply above opportunistic routing algorithms on data dissemination in OppMSNs. DTF-MSN [3] shows a scheme to gather information in the Delay/Fault-Tolerant Mobile Sensor Network based on an improvement of Direct Delivery and Epidemic. The proposal consists of two key components: queue management and data transmission. Queue management decides the importance of messages, and data transmission decides the node with high delivery probability to send messages to. However, the scenario used to evaluate the proposal has only one mobility model, where both source and sink are mobiles nodes, and is far from realistic for the OppMSN application domain. Camara et al. [6] present a good mechanism for the distribution of messages, but the mechanism limits itself to vehicle-to-vehicle and infrastructure-to-vehicle. The work uses only the basic Epidemic routing and there is no comparison with other routing protocols. Recently, Keranen et al. [25] evaluate opportunistic networks with various mobility models and routing algorithms by using the ONE. Nevertheless, the used architecture does not include fixed infrastructure and the results only show the simulation speed.

Therefore, we are interested in investigating towards routing in OppMSNs, which consist of fixed, mobile infrastructures, and mobile nodes with unpredictable movement. Since algorithms are proposed for different optimization objectives under different constraints and scenarios, it is difficult to compare the performance of them all. In this paper, we only select the five most well-known and comparable to investigate. They are Epidemic [12], Direct Delivery (DD) [13], FirstContact (FC) [15], and PRoPHET [16], and Spray and Wait (SnW) [14].

We also improve the ONE simulator for simulations. The ONE includes several opportunistic routing algorithms and mobility models. Researchers can import their own maps and to configure the simulator with their own settings by many parameters, such as speed of mobility, message size, buffer size, and etc. Moreover, the ONE is an open source enabling researcher develop the tool for their own specific objectives.

III. Proposed Opportunistic Mobile Sensor Network (OppMSN)

Most traditional sensor applications are based on fixed and mobile wireless sensor networks, for which the availability of contemporaneous end-to-end connectivity is essential. However, the very recent innovation of mobile phones with different types of onboard sensors and available low power consumption radios has brought on a new interest of using mobile phone as the main part of sensor networks. The network becomes opportunistic, and mainly consists of the existing wireless ad-hoc sensor network and the mobile sensor network.

A. Architecture

The considered opportunistic network is separated into several regions based on communities as shown in Figure 3. In order to link these regions, each region has a base station equipped with long-range communication such as satellite, GSM, Internet. In addition, network architecture of a region consists of the following components: a fixed infrastructure, a mobile infrastructure (e.g. data mules), and mobile nodes.

- *Fixed infrastructure:* Road side units (RSUs) are deployed along main roads of the region. RSUs will be physically integrated in or fixed to the existing infrastructure, like lampposts, GSM base station, or walls. RSUs form an ad-hoc wireless network, acting as a backbone, connecting mobile nodes with central servers or data sinks. The fixed infrastructure can also be used to disseminate information from central servers to the regions. The distance between RSUs is approximately 60 meters, using WiFi to build the network. There are two types of wireless interfaces for the RSUs, short-range Bluetooth and WiFi 802.11. Messages are transferred among RSUs through WiFi. The Wifi interface is also used to connect to buses, trams, cars, and smart phones. Bluetooth is designed for communication between RSUs and regular phones.
- *Mobile infrastructure:* Equipped with WiFi 802.11, buses and trams with known routes and known stops are considered as the mobile infrastructure in OppMSN applications. Since buses and trams move relatively fast, Bluetooth characterized by short-range (< 10 m) and low speed (< 2 Mbit/s) is not an appropriate option for buses and trams.
- *Mobile nodes:* The last component of the heterogeneous architecture consists of mobile phones (used by pedestrians) and a small portion of cars. There is no information of possible paths towards the sink because mobile phones, the majority of networks, move unpredictably. Mobile phones are classified into either smart phones or regular phones. Smart phones typically have both WiFi and Bluetooth interfaces, while regular phones have only Bluetooth. For the same reason buses and trams use WiFi only, cars are equipped with WiFi.

B. Architecture Performance Requirements

Depending on the physical characteristic, each of proposed components has a different degree of performance requirements such as reliability, throughput, latency, and electric power consumption. Fixed infrastructure has unlimited electric power supply, strong and stable signal strength, and large data storages. Therefore, latency and throughput are the most considerable performance requirements, and reliability and power consumption can be ignored. A message should be transferred as fast as possible via the ad-hoc connected network based on fixed infrastructure. Since

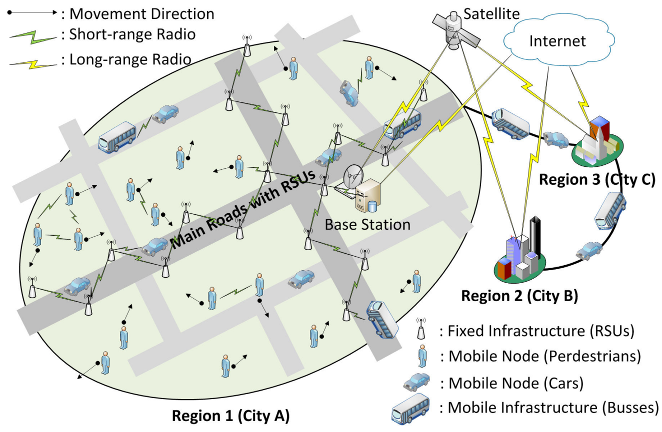

Figure 3. Architecture for Opportunistic Mobile Sensor Networks.

the RSU network is linear lines crossing each other at few points, the bottleneck phenomenon probably decreases throughput and increases latency.

Mobile infrastructure, such as buses and trams, has no constraint on power supply, signal strength, and storage capacity. Thus, mobile infrastructure also has no problem with reliability and power consumption. As buses or trams play a role as messengers shuttling between sources and sinks in the network, latency depends on velocity and distance significantly. In addition, mobile infrastructure may become a bottleneck point because many passengers try to connect to a bus or a tram. As a result, the throughput of mobile infrastructure needs to improve as well.

Since mobile phones suffer limited power supply and intermittent connectivity, power consumption and throughput are the most critical performance requirements. Reliability is another considerable performance requirement because mobile nodes are sparse and dynamic. That some people are not willing to turn on the wireless interfaces all the time also makes the network less reliable. Moreover, velocity and unpredictable movement patterns of mobile nodes deter obtaining low latency and high throughput.

C. Network Operations

When a node sends a message to the data sink (base station) by using an opportunistic protocol, the message is transferred towards the base station by the store-carry-forward paradigm. The message is stored in phones or vehicles, and then forwarded to other nodes during opportunistic contacts. The node receiving the message is either the base station, a car, a phone, or a RSU. The nodes, except the base station, continuously forward the message when in communication range of other nodes. Eventually, nodes may carry the message to the base station. If reaching a RSU, the message usually takes the paths based on connected RSUs to go to the base station.

RSUs with a large storage capacity also act as a relay node in the network. Messages are stored at RSUs for a period of time until they expire due to a limited time-to-live (TTL). In some cases, reliability of event detection is enhanced by aggregating data provided by other sensor devices. A mobile node perhaps receives messages from the fixed infrastructure and then forwards them to other nodes. As a result, a message containing event information will not only be transferred to the base station but also disseminated to nodes in network.

Buses and trams are not only message ferries as described in [24] but also gateways for passengers. Because the contact durations of mobile phones carried by passengers on a bus are quite long, messages may be fully exchanged among the passengers. Furthermore, these messages are stored at the bus and then disseminated to next passengers or delivered to the base station at the last bus stop.

When moving from one region to another, a mobile node will act as a gateway, transferring messages between regions. The transfer will be slow compared to using the fixed infrastructure. As the anticipated application domain is safety in public spaces, (emergency) messages should reach their destination as fast as possible.

D. Mobility Model

To increase the realism of the mobility model, we propose two additional models, Random Shortest Path Map Based Movement (RSPMBM) and Road Side Unit Placement. The new models, together with exiting Map Based Movement, Bus Traveler Movement and Bus Movement, are suitably applied for different types of sensor nodes. This approach represents the heterogeneous nature of reality, with Road Side Units, cars, buses and pedestrians.

We assume that a portion of mobile nodes represents pedestrians wandering around without any specific purpose. The existing Map Based Movement (MBM) provided by the ONE is likely the most suited. MBM is the Random waypoint movement with map-based constraints, in which a mobile node moves from one map node to another by selecting a neighboring map node randomly. This movement is repeated a randomly chosen number of times.

Naturally, people do not just wander around. They want to go somewhere for a purpose, using the shortest or fastest path possible. The choice between walking or taking the car is often decided by the Euclidean distance to the destination. These destinations are very diverse [26], ranging from points of interest in the public domain (e.g. restaurants, parks, offices) to the more private ones (e.g. friends, home, family). Therefore, we propose the new movement model, RSPMBM, to model the behavior of human-like mobility. A node selects an arbitrary destination within a predefined range and then moves along the shortest path. Euclidean distance ranges are configurable in a setting file, for example, the distance ranges can be set $[50, 500]$ and $[500, 5000]$ meters for pedestrians and cars, respectively. Remark that the minimum walking distance of a pedestrian is set to 50 m to ensure every node always travel a little.

It is reasonable to assume that a number of civilians, called as bus travelers, who prefer traveling by bus. Movements of bus travelers and buses are modeled by Bus Traveler Movement and Bus Movement that are also available in the ONE simulator, respectively. A bus traveler compares distance to the nearest bus stop with to the destination to decide whether to take a bus or not. A bus can carry many passenger and shuttles flowing its pre-defined route and timetable.

The new Road Side Unit Placement model is proposed for deploying RSUs on a map, along side roads with a certain distance between each other. The RSUs are stationary and form a wireless ad-hoc network or wireless sensor network.

E. Evaluation Metrics

Four metrics are used to evaluate the aforementioned performance requirements of different routing algorithms. Two of them are metrics implemented in the ONE: delivery probability and latency. Hop-count metric is no longer an informative metric to assess the delivery cost in time and distance in OppWSNs as it is used in connected ad-hoc WSNs. Instead, we define Delivery Speed and Delivery Cost for a more accurate evaluation.

- *Delivery Probability DP:* The total number of successfully delivered unique message, denoted by Q, divided by the total number of created unique messages, denoted by P. Each unique message is created at certain time, and has an unique identification number to be distinguished with others in the network.

$$DP = \frac{Q}{P}. \tag{1}$$

- *Latency (DL):* The average of delays between the moment that unique message i is originated, denoted by Ts_i, and the time when the first replicate of unique message i arrives at the destination, denoted by Td_i. The replicate is a copy of an unique message. The number of replicates depends on the methodology of the routing algorithm, single or multiple-copies.

$$DL = \frac{1}{Q} \sum_{i=1}^{Q} (Td_i - Ts_i). \tag{2}$$

- *Delivery speed (DS):* The average of speeds of the first replicate of unique message i that is sent from the origin to the destination. It is defined by the Euclidean distance, denoted by d_i, divided by latency.

$$DS = \frac{1}{Q} \sum_{i=1}^{Q} \frac{d_i}{Td_i - Ts_i}. \tag{3}$$

- *Delivery cost (DC):* The total number of unique messages including replicates, denoted by R, divided by the number of first replicates successfully arrived their destinations.

$$DC = \frac{P + R}{Q}. \tag{4}$$

Note that latency DL does not take the distance from origins to destinations into account like the delivery speed DS. Therefore, DL only a good metric in scenarios that origins of messages are uniform distributed.

To evaluate the proposed architecture and the proposed mobility model, we use the inter-contact time, first defined by Chaintreau et al. [27]. Inter-contact time is the time interval between two successive contacts of a pair of nodes, from the end of one contact to the next contact with the same node. Inter-contact time represents the frequency of opportunities for nodes to send packets to other nodes. The distribution of inter-contact time has an impact on the performances of different routing algorithms. [27] also shows that the inter-contact times are power-law distributed with the power-law exponent less than one.

IV. Simulation and Evaluation

In order to evaluate our proposed architecture and mobility model, a realistic simulation environment is set up, using a real city map. The results of running selected routing protocols are analyzed and compared to gain a better understanding on performances of existing routing protocols. From that, we may attain implications for future work. We use the ONE simulator [20] that is specially designed for opportunistic networks. It allows users to import maps, configure radios, message size, node speed, etc. The most advantage of the ONE is an open source so that we can flexibly develop new features for better simulation.

A. Environment Setup

The simulation uses the center of the city of Enschede as a realistic setting. In the center of the map, there is the central bus station. The map shown in Figure 4 takes up approximately 3500 by 3000 meters and is exported from Openstreetmap.org. To this map several layers, as submaps, are added for RSUs, roads for cars, paths for pedestrians and routes for buses. RSUs are positioned at the outer and inner ringroads, and four main roads radiating from the center. Cars are restricted to roads, but pedestrians may roam everywhere. Buses follow routes from the real city bus system. Roads in the ONE simulation have zero width. To overcome this limitation, roads are defined by two parallel routes as the lanes of a real road. In this way, communication with vehicles or pedestrians at both sides of the road is more realistic.

The simulation is carried out with 336 RSUs manually fixed on main roads, 50 cars, and 600 pedestrians moving around inside the city. The initial position of cars and pedestrians is randomly distributed. There are quite many bus lines in the city but only four are chosen because others have routes overlapping the RSU lines. Since RSUs can transfer messages to the base station much faster than buses do, buses that run along RSU lines have small contributions to the message delivery. Each bus line has two buses shuttling their routes. Since our basic goal is to investigate the contribution of pedestrians in disseminating data, only a small portion of cars, 50 over 650 mobile nodes, are simulated in the simulation. We also assume that the speed of pedestrians remains almost constant, $0.5 - 1.5$ m/s. Therefore, the mobility speed has a minor effect on performance results.

Since our proposed architecture also aims to reduce the use of mobile services for message exchange, we only consider available short-range interfaces, particularly Bluetooth and WiFi. All mobile phones have Bluetooth Version 2.0 at 2 Mbit/s net data rate with 10 m radio range, while smart phones have only WiFi interface at net data rate of 10 Mbit/s with 60 m radio range. We assume that fifty percent of pedestrians own smart phones and the rest uses normal phone. RSUs have both interfaces. The remaining nodes, cars and buses, use WiFi only, because they move at speeds that make Bluetooth communication unrealistic.

From the 600 pedestrians, 500 move with a purpose, while 100 are just strolling. Because cars likely possess predetermined routes, RSPMBM would be most suited. Buses follow fixed routes with predefined stops, and are modeled with the Bus Movement mobility model. Finally, pedestrians in buses are modeled with the Bus Traveler Movement model.

Data dissemination in the above heterogeneous scenario is simulated with a number of opportunistic routing protocols: Epidemic [12], Direct Delivery (DD) [13], FirstContact (FC) [15], and PRoPHET [16], and Spray and Wait (SnW) [14] with the number of copies (n) to be 6. This setting value is default in the ONE simulator. Since Message Ferry (MF) [24] is only useful for buses to transfer messages among base stations of cities, in our simulation with a single city, buses are just considered as a vehicle to transport passengers and do not implement MF.

Messages are generated every $25 - 35$ seconds by random cars and pedestrians. RSUs do not generate messages, but act as a communication backbone. Messages may contain pictures, video and soundbites, and are 500 KBytes to 1 MBytes in size. Suppose that memory capacity is consistent with kinds of nodes, the buffer of normal mobile phones is set to 5 MB, and smart phones, cars, RSUs, and buses have 50 MBytes buffers. We also remarked that increasing buffer size of normal phones up to 50 MBytes affects a little bit on network performance.

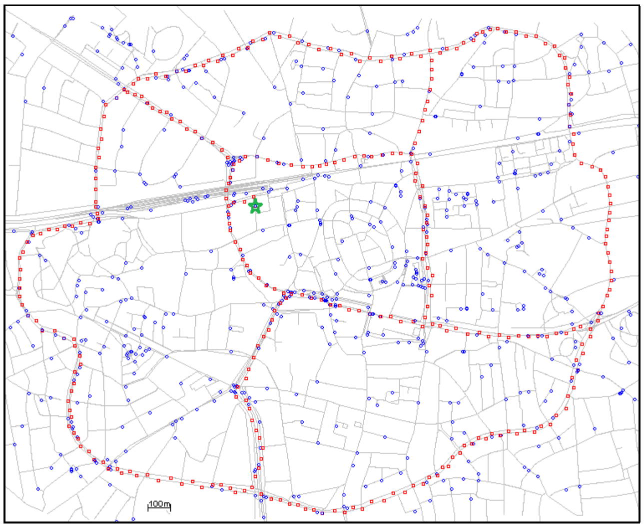

Figure 4. Inner-city of Enschede.

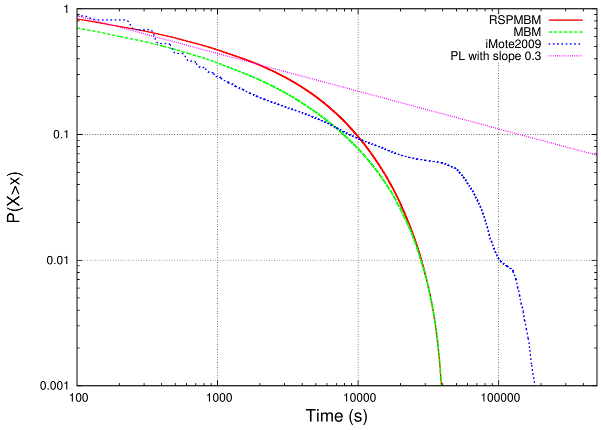

Figure 5. Inter-contact times for RSPMBM compared to the iMote trace.

B. Architecture and Model Evaluation

Figure 5 plots the complementary cumulative distribution (CCDF) of the inter-contact times. The graphs show that the inter-contact time distribution of RSPMBM has a power-law distribution with the exponent approximate 0.3 and similar to the real iMote trace [28]. This power-law distribution does contradict the exponential decay implied by previous mobility models that have been used to design routing algorithms (see [27]). Because the exponent and shape of the distribution may vary between environments, we did not configure parameters to produce the exact same exponent and shape as the iMote trace. Note that the match between the iMote trace and RSPMBM in the first two thirds of the graph. The difference in the last part of the graph is due to the longer trace (in time) of the iMote, leading to more contacts with low distribution probabilities. RSPMBM has shorter contact times due to the RSU communication backbone. In other words, nodes in our simulation environment meet one another more frequently that those in the iMote experiment.

Figure 5 also shows the inter-contact time distribution for MBM used in the Enschede City Scenario (ECS) for comparison. Surprisingly, both RSPMBM and MBM produce similar tails of distribution (exponent coefficients are about 0.3). However, the inter-contact time distribution of RSPMBM has higher probability than that of MBM. This is expected, inter-contact times usually get shorter with increasing reality [20].

C. Opportunistic Routing Algorithm Evaluation

Time-to-live (TTL) is an important variable for data dissemination, and strongly influences data delivery probability, latency, delivery speed, and delivery cost in opportunistic networks. In safety applications, emergency messages should be delivered with high probability, low latency, and high speed. Otherwise, the information might be useless after a certain period. Therefore, assigning appropriate value to TTL to drop obsolete messages probably save a lot throughput. Though TTL has a huge impact on the performance of routing protocols, it is hardly studied in existing literature. We will investigate the influence of TTL on delivery probability, latency, speed, and costs of messages.

Figure 6 shows the delivery probability of each routing algorithm as TTL in the scenarios increases from 10 to 300 minutes. In the graph two very different trends in delivery probability can be observed. DD, FC and SnW have increasing delivery probability with increasing TTL, with a highest gain in the lower TTL values. This is as one would expect. The longer the TTL of a message, the more opportunities for message transferring. Counter-intuitive is the decreasing delivery probability with increasing TTL for Epidemic and PRoPHET. This is explained as follows. Epidemic and PRoPHET are multi-copy, thus the number of relayed messages increases exponentially when TTL is long. Eventually, with a limited buffer and limited contact duration, the delivery probabilities of Epidemic and PRoPHET will dramatically suffer. This explanation is reconfirmed in Figure 9, which depicts the delivery cost for each routing protocol. We also remarked that decreasing message size or increasing buffer size lessens flooding effects on Epidemic and PRoPHET. However TTL still strongly influences their deliver probabilities.

Figure 7 plots the average latency of message delivery as TTL increases. From the graph, one can see that increasing TTL results in increasing delays of message delivery. This is as expected. Since flooding the network with messages, Epidemic scores best. Although Epidemic has the lowest delivery probability at high TTL values, when a message reaches its destination, the message will have low latency. Direct Delivery scores lowest with high latency. DD delivers messages directly to the destination. So it may take some

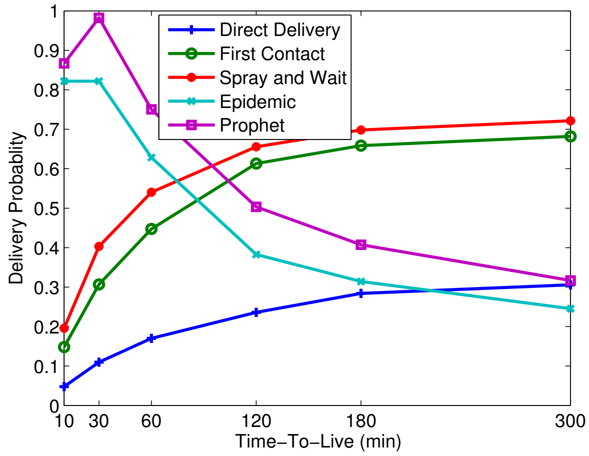

Figure 6. Message delivery probability.

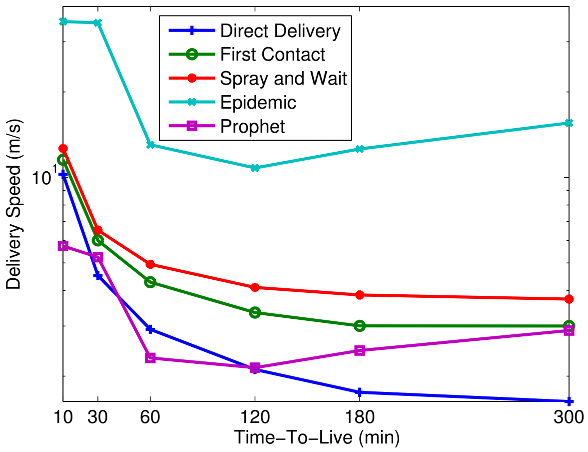

Figure 8. Average speed of message delivery.

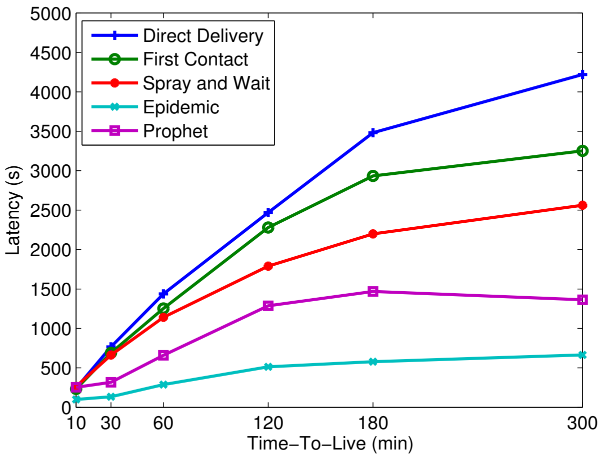

Figure 7. Average latency of message delivery.

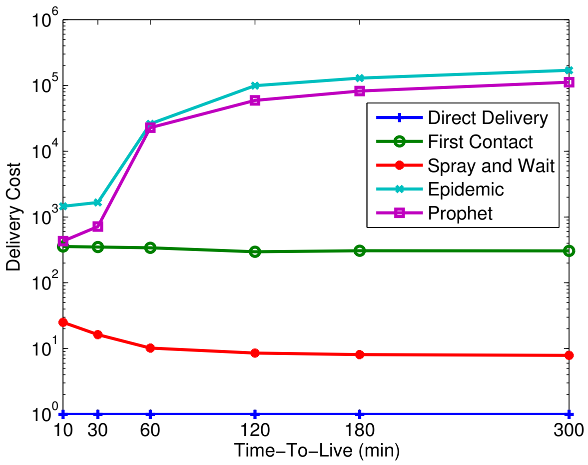

Figure 9. Delivery cost.

time for this opportunity to happen.

The speed of message delivery is depicted in Figure 8. The speed decreases sharply in the first part of the graph for all protocols and then remains almost constant. For 10-min TTL, only messages near the base station or RSUs can reach the destination. Other messages would be dropped before arriving at the base station. Increasing TTL causes more messages farther away from the base station to be delivered. This explains why the average delivery speed declines sharply. However, when TTL is greater than 60 minutes, most messages have sufficient lifetime. Therefore, increasing TTL further does not affect the delivery speed.

The delivery speed of Epidemic and PRoPHET goes up slightly when TTL is greater than 120 minutes. Due to overhead, there are fewer messages that could be delivered. Hence, the average delivery speed rises slightly again.

Epidemic has the highest delivery speed since it floods messages over the network. DD has the lowest delivery speed on account of sending messages only when mobile nodes encounter the base station.

As PRoPHET has the second lowest latency in Figure 7, one would expect it to have the second highest delivery speed. On the contrary, the graph in Figure 8 shows that PRoPHET has the lowest delivery speed when TTL is below 120 minutes. The reason lies in the fact that PRoPHET transfers messages based on the frequency of node encountering, called delivery predictability. Owing to the RSU connected network, most nodes have almost the same delivery predictability. Consequently, messages are wastefully transferred around before reaching the destination. In such way, even the average delay of a message is low, but the Euclidean distance from its source to the base station is short too. That is why the delivery speed of PRoPHET is low even though its latency is not high. This behavior

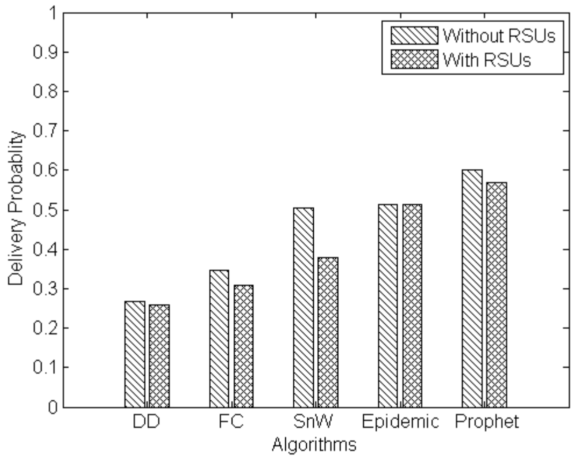

Figure 10. Delivery probability.

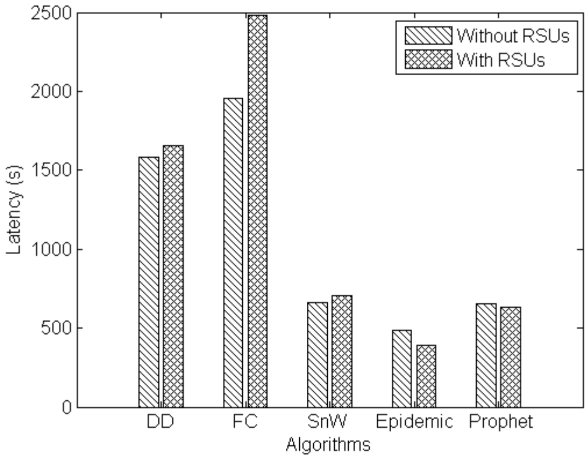

Figure 11. Latency.

also proves that delay of message delivery is not sufficient enough to evaluate quality of message delivery. However, the delivery speed of Direct Delivery even gets lower than that of PRoPHET when TTL is above 120 minutes. This is expected. When TTL increases very high, DD gives higher delay but almost constant delivery probability as in Figure 7 and 6 respectively.

Because the majority of nodes have limited power supply, the delivery costs of opportunistic routing algorithms must be taken into account. The delivery cost represents the ratio between the number of total transmissions needed over that of successfully delivered messages. Figure 9 shows that Epidemic and PRoPHET have the highest delivery cost because they maximize the opportunities of message delivery by replicating copies of messages as much as possible. DD and SnW have the least overhead, as DD has only one single copy of a message and SnW has 6 copies of messages at maximum. Clearly DD has the lowest delivery cost of all routing algorithms. The delivery costs for Epidemic and PRoPHET increase sharply with increasing TTL, but stabilize after a while. The reason is that only a limited number of messages can be transferred during the limited contact duration.

D. RSUs' Assistance Evaluation

To evaluate the advantages of RSUs in the opportunistic network, we investigate the performance of algorithms in both cases, with and without 336 RSUs. For each case, algorithms' performance will be evaluated based on four aforementioned metrics: delivery probability, delivery latency, delivery speed and delivery cost.

To make simulation more realistic, we randomly categorize messages into 5 levels of priority, from 1 (highest) to 5 (lowest). The priority means the importance or urgency of messages. Importance information, such as fire detection, should be delivered rapidly. Otherwise, it is too late, and the information is useless. It makes sense that a message with higher priority should be assigned lower time-to-live. In particular, the time-to-live value in minute is defined corresponding to message priority as in Table IV-D for our simulation.

Priority	1	2	3	4	5
Time-To-Live (min)	10	30	60	120	180

Table I
MESSAGE PRIORITY AND CORRESPONDING TIME-TO-LIVE

Such TTL assignments will significantly improve delivery performance when being combined with some buffer management. For example, Fathima and Wahidabanu [29] manage buffers by dividing messages into three sub-buffers: high priority, medium priority, and low priority. Messages with specific priority should be stored in corresponding buffer.

By intuition, we mistakenly foresaw that the present of RSUs would improve the delivery probability performed by any routing algorithm. However, simulation result in Figure 10 shows that the delivery probabilities can be worse in case of adding RSUs. This surprising conflict can be explained through studying the naive methodology of the algorithms. Since DD only transfers messages to their corresponding destinations, the existing of RSUs just scams mobile nodes with more header-list exchanges, which help nodes check the message destinations of each other. Although this wasting time is little, it still results in increasing the probability of dropped messages due to TTL, and decreases a certain number of delivered messages as well as increase the latency as shown in Figure 10 and 11, respectively. This effect is more serious for FC and SnW because both algorithms have more wasteful message

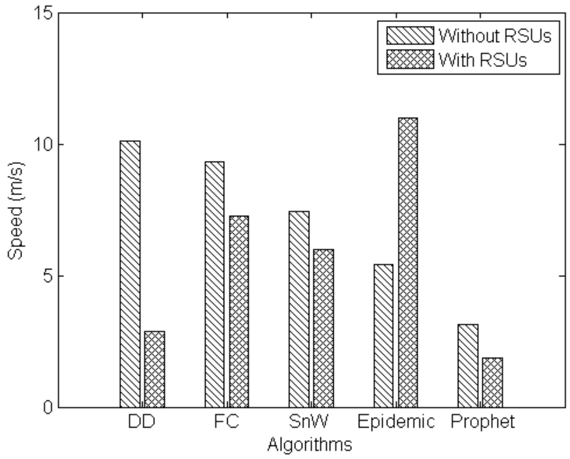

Figure 12. Delivery speed.

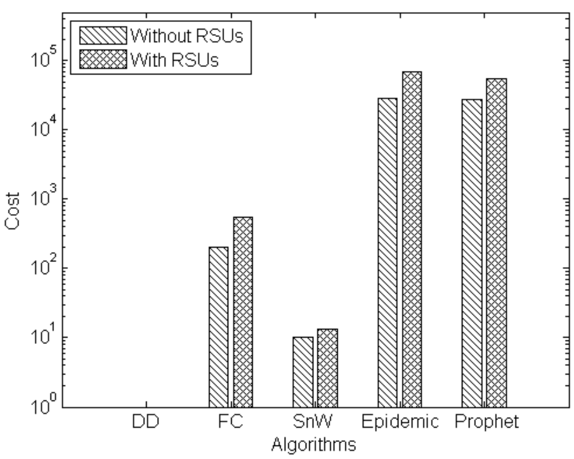

Figure 13. Delivery cost.

exchanges with enormous 336 RSUs. Remark that the hitting time of two mobile nodes is less than that of a mobile node and a RSU [14]. Therefore, both FC and SnW have lower delivery probability and higher latency in case of adding RSUs, see Figure 10 and 11.

PRoPHET also suffers from the wasting contact times with RSUs since the delivery predictability of RSUs depends on mobile nodes, not RSUs them self. In other words, transferring messages based on the delivery predictability is not suitable for stationary nodes. This explains why Prophet has the lower delivery probability in case of adding RSUs. Conversely, Epidemic has the least effect from adding RSUs in term of delivery probability and even has shorter latency since Epidemic can infinitely flood RSUs with messages. In such way, messages can be delivered faster via the connected RSU's network as shown in Figure 11.

Figure 12 shows the delivery speed of the algorithms. By comparing between Figure 11 and Figure 12, we observe that, in general, shorter latency is corresponding to higher delivery speed. However, figures show that Prophet has shorter latency but also lower speed. Again, this illustrates that latency does not totaly reflect how fast a message is delivered as we discussed. So, the extra contacts with RSUs also slows down the speed of message delivery for Prophet.

Results of delivery cost shown in Figure 13 are what we expected. Since adding RSUs leads to having more nodes in the network, there are more opportunities for transferring message copies around. Therefore, the delivery cost, which is based on the number of transmissions, increases for all algorithms, except DD because it only sends messages to destination nodes.

In conclusion, most compared algorithms cannot improve their performance in terms of delivery probability, latency, speed, and cost by adding RSUs since they are mostly designed for network of which majority are mobile nodes.

V. Conclusion and Future Work

In this paper, we have proposed a heterogeneous architecture comprising fixed infrastructure, mobile infrastructure, and mobile nodes. In addition, we propose a realistic mobility model and metrics. Several well-known opportunistic routing protocols are tested with this architecture under constraints of limited buffer size, message size, time-to-live, and unpredictable movement. Our observation shows that none of the evaluated protocols performs well with a heterogenous scenario, such as the one described in this paper. We also observe that most of the algorithms do not improve their performances when adding RSUs. Since a single simple routing algorithm does not suffice to improve the overall message delivery performance, a contribution of several algorithms should be considered:

- Road Side Units (RSU), as used in the backbone network, should not only carry received information to a central server but also disseminate information to nearby passing nodes. This communication shortcut leaves the base station out of the loop and contributes a better delivery speed and delivery cost. The Epidemic routing protocol with a flooding control mechanism is best suitable for the RSU network if delivery cost is not the most important.
- Buses, which act as data mules or message ferries, have a mobility pattern based on fixed routes and time schedules. The Message Ferry routing protocol is most appropriate.
- Pedestrians and cars are best served by stochastic and context-based schemes. However, exchanging messages between nodes that use different routing protocols is a challenge. For examples, nodes running PRoPHET fail to update the delivery predictability of nodes running Epidemic due to the unavailability of delivery predictability in Epidemic router.

We also plan to take message priority into consideration. Because designing an optimal routing protocol with a delivery probability of 100% under all conditions is difficult, prioritizing messages becomes a necessity. Message prioritization relies on the importance of information, creation time, or source location. Priorities must be defined by a specific application, for instance, public safety applications define the priority based on the source location, creation time, and seriousness of detected events. One last point of our concern is the security and privacy of information. A leading principle should be that the creator owns the data and decides how the data can be used by others. However, one may argue that in situations of emergency this principle may be overruled by authorities. This issue will be addressed in future research. Currently we are developing a heterogeneous algorithm, termed as *Unified* [30] and a testbed is planned to implement and evaluate the proposed heterogeneous algorithm.

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