Investigating the Performance of Delay-Tolerant Routing Protocols Using Trace-Based Mobility Models

Md. Khalid Mahbub Khan, Muhammad Sajjadur Rahim, and Abu Zafor Md. Touhidul Islam

Abstract The mobility patterns of nodes significantly influence the performance of delay-tolerant network (DTN) routing protocols. Trace-based mobility is a class representing such movement patterns of nodes in DTN. This research analyzes the performance of DTN routing techniques on trace-based mobility regarding delivery ratio, average latency, and overhead ratio. Three real traces: MIT Reality, INFOCOM, and Cambridge Imotes are implemented on five DTN routing techniques: Epidemic, Spray and Wait, PRoPHET, MaxProp, and RAPID. For more explicit realization, Shortest Path Map-Based Movement from synthetic mobility model has also experimented with the traces. The Opportunistic Network Environment (ONE) simulator is used to simulate the considered protocols with these mobility models. Finally, this research presents a realistic study regarding the performance analysis of these DTN routing techniques on trace-based mobility along with Shortest Path Map-Based Movement by considering the variation of message generation intervals, message Time-To-Live (TTL), and buffer size, respectively.

Keywords Delay-tolerant network · Routing protocol · Trace-based mobility model · Performance analysis · Opportunistic network environment simulator

1 Introduction

Delay-tolerant networking (DTN) architecture has been proposed to address the application drawbacks in dynamic networks, which may experience topological

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diversity due to the intermittent connectivity among nodes. Several reasons exist behind such intermittent connections of nodes in DTN: bounded coverage range of nodes, extensive distribution of mobile nodes, restriction of resources (i.e., energy), higher interferences or other medium impairments, etc. These characteristics make the DTN scheme a perfect replacement for conventional Mobile Ad Hoc Network (MANET). MANET architecture is not suitable for those applications since an instantaneous path from source to destination nodes is required for transmitting data. Also, any delay handling mechanism to account for these delays because of intermittent connectivity of nodes is absent in MANET. Therefore, higher latency decreases the data delivery rate in these cases, whereas DTN architecture improves the success rate of data delivery by exploiting the "Store-Carry-and-Forward" strategy on mobile nodes suffering intermittent connections to each other. Within this approach, nodes store data on limited buffer storages, while connectivity is unavailable and bears data for an interim period to forward before the connection of nodes with the target node is available. Thus, DTN can be an excellent option to deliver data successfully in those networking scenarios intended to operate in heterogeneous mobile networks, interplanetary communications, rural communications, extreme and emergency terrestrial environments, viz. natural disaster-affected areas, etc. [1, 2].

Several routing protocols have been proposed for DTN scenarios to improve the data delivery rate considering minimum latency and overhead. The flooding-based protocol can be considered the first-generation protocol where the message is replicated uncontrollably. Epidemic [3] is an example of a flooding-based protocol. Later, message replication was restricted to next-generation protocols. Spray and Wait [4] is a notable instance of this type of protocol. Then, a probabilistic concept is adopted in the message routing strategy. Probabilistic Routing Protocol using the History of Encounters and Transitivity (PRoPHET) [5] protocol is an example of such probabilistic protocols. Resource allocation-based and schedule-based protocols are the posterior protocols. Resource Allocation Protocol for Intentional DTN (RAPID) [6] and MaxProp [7] are examples of such routing techniques. Although such protocol's application perspectives are different, researchers have been investigating better routing solutions for DTN scenarios.

However, the movement pattern of nodes' is an essential factor to consider in DTN architecture. The message transmission time depends on the nodes' movement pattern and the distance between the source and destination node. This transmission time may vary from a few minutes to more hours or multiple days. Accordingly, the performance of data delivery of the routing technique significantly depends on the selection of a proper mobility pattern [8]. Moreover, the frequency and duration of the contact are influenced by the movement pattern of nodes. The nodes' movement model depends on various factors such as the entire networking area, map of the street, and nodes' speed. Mobility patterns can be categorized into two types. The first type is synthetic mobility pattern which is a statistical model. In this case, mobility pattern is generated according to particular rules. Shortest Path Map-Based (SPMB) Movement [9] is one example of such a model. These synthetic mobility models are mainly specified for a group of users.

On the other hand, real trace-based mobility is another type of movement pattern. These real traces are developed from many real-life applications and exhibit the actual behavior of nodes in a specific environment. Several real traces are available in an online-based repository known as the CRAWDAD project [10]. Traces are established on contact traces and GPS traces. A finalized contact list is supported by a contact trace when two or more nodes are involved in a contact. Contact's start time and end time are also included there. Differently, the location of nodes is given for a specific duration in GPS traces. However, unfortunately, some application restrictions have been realized in real traces. New scenarios, which are outside the collections, are not supported by traces.

Furthermore, traces have a fixed size, so it is impossible to extend the size of the traces, and they are unable to support any variation from user contexts. So, traces would not consider if the users were moving in challenging and troubling environments. Apart from this, the utilization of traces in simulation is less cost-effective as external files are necessary to read the information related to contacts. In comparison, synthetic movement models offer additional functionalities. These models support different new scenarios and allow the parameters to be adjustable. Accordingly, if the change of any network-related attributes, viz., if the network is extended due to increasing node density, synthetic mobility models can afford that is absent in real trace-based mobility models [11].

This study has investigated a comparative performance analysis of several DTN routing protocols considering three real traces: MIT Reality, INFOCOM, and Cambridge Imotes. Shortest Path Map-Based Movement from synthetic mobility is also considered in our study for simplifying the comparison. Opportunistic Network Environment (ONE) Simulator [12] is used as the simulation tool to perform all the simulations. We have analyzed the performances of simulated protocols considering three traces and one synthetic mobility model based on three performance metrics: delivery ratio, average latency, and overhead ratio. The remaining portion of this paper consists of: Relevant literature study is provided in Sects. 2 and 3 which presents a brief description of considered mobility models in this research, and Sect. 4 gives a short review of experimented DTN routing protocols. An explanation regarding the simulation environment and necessary parameters is given in Sect. 5, whereas Sect. 6 analyzes the comparative performances of simulated routing protocols. Lastly, Sect. 7 contains the conclusions and some directions for future research works.

2 Related Works

Real trace-based mobility and synthetic mobility models are considered in many research works by researchers. Besides, performance analysis of DTN routing protocols from various perspectives also gained attention in various researches. In [13], the authors have considered performance metrics such as delivery ratio, latency, buffer occupancy, and hop count to evaluate the performance of several DTN routing protocols. Only Random Waypoint from synthetic mobility is used as the mobility model in this case. A comparison of several synthetic mobility models such as Shortest Path Map-Based, Map-Based Movement, and Random Waypoint is presented from various perspectives in [14]. Nevertheless, real trace-based mobility models are unaddressed here. Furthermore, the authors in [15] have demonstrated the energy consumption of the existing DTN protocols using three synthetic mobility models, namely Random Walk, Random Waypoint, and Shortest Path Map-Based movement. Performance comparison of those synthetic models for simulated DTN protocols is also given. Although several mobility models are examined, the absence of any real traces can be considered the limitation of this work. On the other hand, two experimental scenarios are considered to analyze the performance of four different conventional DTN routing techniques on the Tirana city map based on four performance metrics in [16]. Except for any real traces, Shortest Path Map-Based model is chosen here. In [17], a performance analysis of social-based routing protocols with traditional DTN routing protocols is investigated. This study considers only the Shortest Path Map-Based Movement model, which is an example of a synthetic mobility model. This performance analysis is conducted using three performance metrics: delivery ratio, average latency, and transmission cost. In addition, the impact of increasing node density and TTL is considered. However, the trace-based mobility models are excluded from this research. Another performance comparison of synthetic mobility models is exhibited in [18] without including any real trace. In this study, existing DTN routing techniques are involved. Moreover, performance analysis of several DTN routing protocols along with the energy efficiency is studied in [19]. Like the previous works, real traces were absent in this study, while only the Shortest Path Map-Based Movement model is adopted as the default mobility model. These pitfalls of the above works motivated us to investigate the impact of real traces on the performance of DTN routing approaches.

3 Mobility Models Under Investigations

In our study, we have included three real trace-based mobility models: MIT Reality, INFOCOM, and Cambridge Imotes. Shortest Path Map-Based Movement from synthetic mobility model is also considered in this research to get a comparative idea about the outcomes. A brief explanation of the above-mentioned mobility models is given in this section.

MIT Reality is a trace that is campus-oriented. It is based on 97 Nokia 6600 cellphones which are interconnected through the Bluetooth interface. In this trace, the contact information was obtained from the course-wise faculty members and MIT students in the 2004–2005 academic year. This contact information was formed not only from the data transmission among participants but also from the location and proximity of the participants. The total duration of this trace is 246 days [20].

INFOCOM trace is also recognized as Haggle 3 project trace. This trace originated from a conference having the same name and sponsored by IEEE. This conference was organized in 2005. Here, 41 volunteering participants carried the same number of Intel Motes (Imotes) devices through Bluetooth connectivity. Later, the organizers associated 98 participants with the same number of Imotes devices in 2006, and the dataset found from there is known as INFOCOM 6. The entire duration was 3 days for both INFOCOM 5 and INFOCOM 6. INFOCOM 5 is endorsed within this study so we would use INFOCOM to identify INFOCOM 5 trace [11].

Cambridge Imotes is another campus-based trace. In this trace, 36 Imotes were provided to the same number of participants in the University of Cambridge campus area. Such devices were set up in the most well known and trendy places on campus for 10 days. Bluetooth interface was used here as the communication technology. It is also familiar as Haggle 4 project trace [11].

Shortest Path Map-Based Movement is a synthetic mobility model. It is a more realistic model than other map-based movements. Here, map data that is fixed provides random paths where nodes are moving randomly. Random points on the map are chosen by the nodes based on their recent positions. Nodes further try to discover and pursue the shortest path to the random points. The current locations construct the shortest path of these random points following Dijkstra's algorithm. The target random points are randomly selected, or a list known as a Point of Interest (POI) is formed. This list is chosen depending on the popular real-life places, viz., well-known tourist places, shops or restaurants, etc., which are prominent and trendy [12].

4 Investigated DTN Routing Protocols

We have experimented with five DTN routing protocols: Epidemic, Spray and Wait, PRoPHET, MaxProp, and RAPID in this research. This section describes the basic mechanisms of these protocols.

In Epidemic protocol, uncontrolled replication of messages takes place. In this strategy, the source node replicates the message it has continuously. Then, it forwards the message copies to those encountered nodes that have not received any copy of this message yet. In such a manner, the intended target node will receive the message copy eventually. The main drawback of this routing strategy is that multiple copies of the same message will flood the network. Furthermore, another shortcoming of Epidemic is that the concept of limited resource utilization (i.e., bandwidth, buffer space, etc.) is absent in this approach. So, to deliver data successfully in a network, it will consume a significant amount of network resources. This deficiency makes Epidemic the worst candidate for routing in DTN [3].

Spray and Wait protocol exploits the limited replication concept in message forwarding. In this case, a limited number of message copies are forwarded to a similar number of relay nodes. Source node will forward L copy of the message to the L relays. Here, L denotes the maximum number of message replicas that are allowed to be dispatched. The value of L is influenced by some factors, viz. network's node density, etc. Spray and Wait strategy incorporates two phases [4]:

Spray Phase: In the "Spray" phase, a message-carrying node will forward L replicas of a message to the L number relay nodes.

Wait Phase: L relay nodes will wait by carrying L replicas of the message until their expected encounter with the destination node to deliver the carried replicas of the message. This phase is known as the "Wait" phase.

Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) is a forwarding protocol where the message carrier node maintains a set of probabilities. Nodes' actual real-world confrontation likelihood is considered in this approach. While a meeting with a message carrier source node will take place, a message will be forwarded to the encountered nodes depending on probabilities. The encountered node which has a higher chance of delivery will obtain the message first [5].

In the MaxProp protocol, specific schedules are assigned and prioritized to forward data packets. A message carrier node maintains a ranked list of data packets to determine which packet will be forwarded or dropped on a primitive basis. This ranked list depends on the cost computed from the source node to all destined target nodes and reflects the message delivery probability estimation. The packet preference is maintained in the MaxProp protocol depending on the minimum hops count by avoiding the multiple version reception of the same message [7].

The resource allocation problem of the DTN environment is addressed in Resource Allocation Protocol for Intentional DTN (RAPID) protocol to improve the routing performance. In such a case, DTN architecture is assumed as a scheme that is utility-driven. This utility-driven scheme maintains a utility function responsible for referring a utility value U_i to each data packet following the parameter related to the packet routing. U_i acts as the expected contribution of packet i against the identified forwarding parameter. Into this utility, the packet which results in a higher increase will be replicated earlier in the RAPID protocol. RAPID will copy every message as long as the network resources, i.e., bandwidth, etc., permit [6].

5 Simulation Environment

We have analyzed the influence of the selected mobility models (both synthetic and trace-based) on the examined routing protocols on behalf of three performance metrics: delivery ratio, average latency, and overhead ratio. To do so, we have varied the values of message generation intervals (5–15 s to 45–55 s), message TTL (6 h–3 d), and buffer size (5–25 MB) successively to run simulations on the configured protocol and mobility models. When one parameter is varied, the remaining are kept fixed (message generation interval: 25–35 s, TTL: 1 d, and buffer size: 5 MB). Table 1 demonstrates the necessary parameters essential for simulations, while Table 2 represents the critical information related to selected mobility models (trace-based and synthetic). The overall simulation area is considered as 4.5×3.4 km. As the traces are campus or conference venue aligned, a single group of pedestrian is treated as mobile nodes carrying handy mobile devices. The speed of mobile nodes is assumed as 0.5–1.5 m/s. However, the number of mobile nodes is kept fixed according to the real traces. For the convenience of comparison, the same number of mobile nodes is used in the synthetic mobility model—Shortest Path Map-Based movement. Bluetooth technology is utilized as the communication interface among the mobile nodes. Due to justification and evaluating the performance comparison of simulated protocols on selected real trace-based and synthetic mobility models, we have normalized the entire simulation as 3 days. All the simulations are performed on the map of Helsinki city (the default map for ONE simulator).

Table 1 Necessary parameters for simulation [21]

Parameter	Value
Simulation area	4500 × 3400 m
Simulation time	3 d
Routing protocols	Epidemic, Spray and Wait, PRoPHET, MaxProp, and RAPID
Number of message replica (for Spray and Wait)	10
Seconds in time unit (for PRoPHET)	30
Mobility models	MIT, INFOCOM, Cambridge Imotes, and Shortest Path Map-Based
Interface type	Bluetooth
Transmit speed	2 Mbps
Transmission range	10 m
TTL	6 h, 12 h, 1d, 2 d and 3 d
Message generation intervals	5–15 s, 15–25 s, 25–35 s, 35–45 s and 45–55 s
Buffer size (MB)	5, 10, 10, 15, 20, 25
Message size (MB)	1

Table 2 Parameters related to mobility models (trace and synthetic mobility) [21]

Mobility	Type	Number of nodes	Duration
MIT reality	Trace/Campus	97	3 d
INFOCOM (Actually INFOCOM 5, also known as Haggle 3)	Trace/ Conference	41	3 d
Cambridge imotes (Haggle 4)	Trace/Campus	36	3 d
Shortest path map based	Synthetic mobility	100	3 d

6 Discussion on Simulation Outcomes

This section provides a brief discussion and analysis of simulation outcomes. We have adopted three performance metrics: delivery ratio, average latency, and overhead ratio to analyze the performance of the simulated DTN routing protocols on the considered mobility models.

Delivery Ratio: This metric indicates the ratio between the number of messages perfectly delivered to the destined targets and the total number of source-generated messages. Since delivery ratio reflects the success rate of message delivery, it is expected to be higher for a network. Figures 1, 2 and 3 demonstrate how the delivery ratio is changed with the variation of message generation intervals (5–15 s to 45–55 s), TTL (6 h–3 d), and buffer size (5–25 MB), respectively, for the selected mobility models on the simulated DTN routing protocols.

Figure 1 represents that the delivery ratio increases gradually for all mobility models on simulated protocols with the increase of message generation interval (5–15 s to 45–55 s). Here, TTL and buffer size are kept fixed at 1 d and 5 MB, respectively. Shortest Path Map-Based mobility has the highest delivery ratio than others for all protocols in this case. So, this synthetic mobility model has a higher delivery ratio than the real traces here. In addition, the limited replication strategy makes Spray and Wait as well as MaxProp the best performer for delivery ratio than other protocols, and they both exhibit a higher success rate of message delivery for the Shortest Path Map-Based Movement model. On the other hand, MIT Reality trace for Epidemic

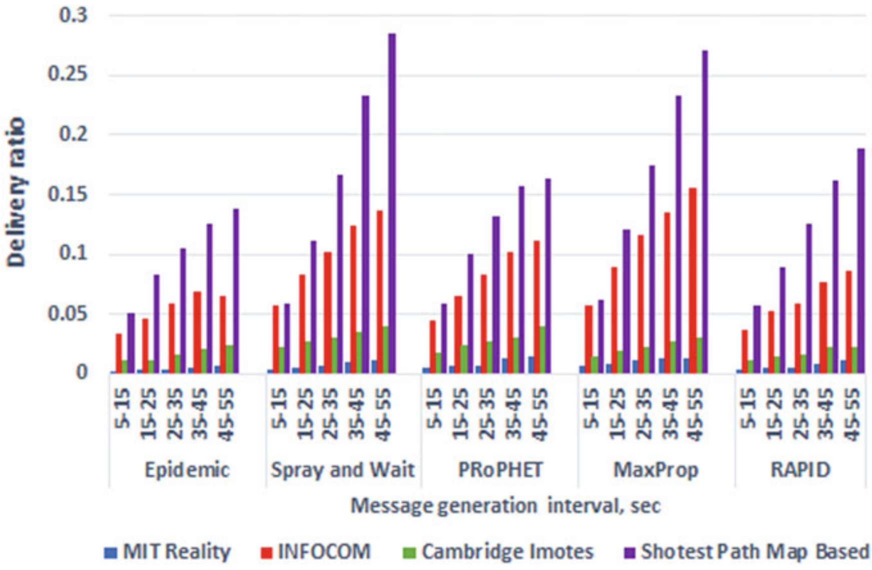

Fig. 1 Delivery ratio versus message generation interval

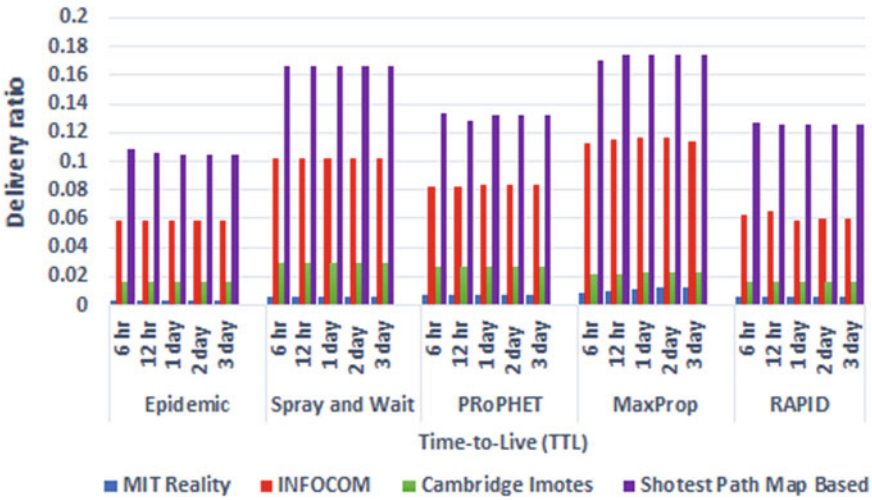

Fig. 2 Delivery ratio versus TTL

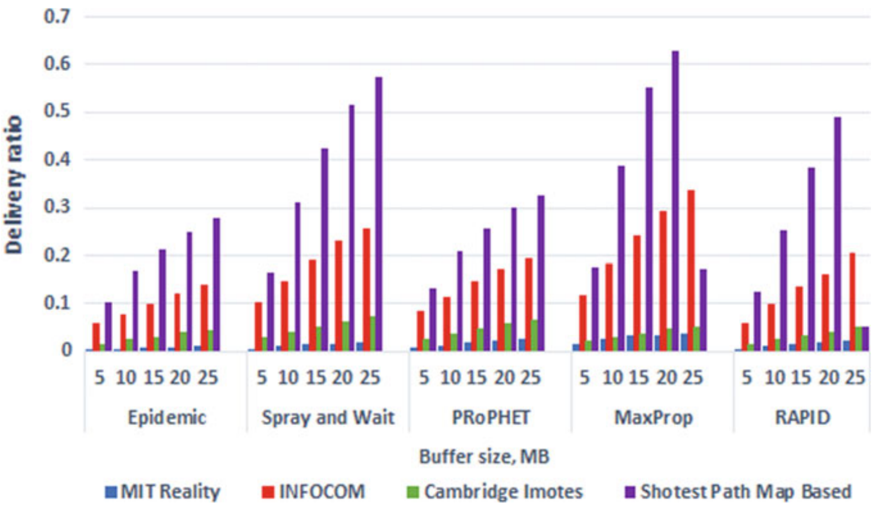

Fig. 3 Delivery ratio versus buffer size

protocol experiences the lowest value of the delivery ratio. In this case, the flooding-based forwarding strategy to route messages in Epidemic reduces the success rate of message delivery.

Figure 2 clarifies that the synthetic mobility model—Shortest Path Map-Based has the highest delivery ratio than the real traces with varying TTL (6 h–3 d). Here, message generation interval and buffer size value are maintained fixed at 25 s–35 s and 5 MB, respectively. Both Spray and Wait and MaxProp protocols have the highest delivery ratios in the Shortest Path Map-Based mobility. But between these two protocols, the MaxProp has a slightly higher delivery ratio. So, MaxProp protocol in the investigated synthetic mobility is the best performer for delivery ratio. In opposition, MIT reality for Epidemic protocol shows the worst performance for delivery ratio, similar to the prior result.

Similar to Figs. 2 and 3 provides the same result for delivery ratio with increasing buffer size (5–25 MB). Here, MaxProp protocol for Shortest Path Map-Based Movement model shows the highest delivery ratio among all protocols with real traces. Epidemic protocol for MIT Reality trace is the worst performer in this case. Here, message generation interval and TTL are kept constant at 25 s–35 s and 1 d, respectively.

Average Latency: Average delay computes the average value of the time differences among the generation of the messages (which are delivered successfully) at sources and their delivery to destination nodes. For efficient routing of messages in a network, the value of this metric requires to be small. Figures 4, 5 and 6 indicate the average latency of simulated protocols on the implemented mobility models with varying message generation intervals (5–15 s to 45–55 s), TTL (6 h–3 d), and buffer size (5–25 MB).

From Fig. 4, it is clear that the MaxProp protocol configured with MIT Reality trace has the highest latency. In contrast, INFOCOM on Spray and Wait protocol exhibits the lowest latency making it the best performer in terms of delivery delay. TTL and buffer size are set at 1 day and 5 MB, respectively, as with the previous cases.

MIT Reality for MaxProp protocol exposes the highest latency for increasing the message lifetime (6 h–3 d), while message generation interval (25–35 s) and buffer

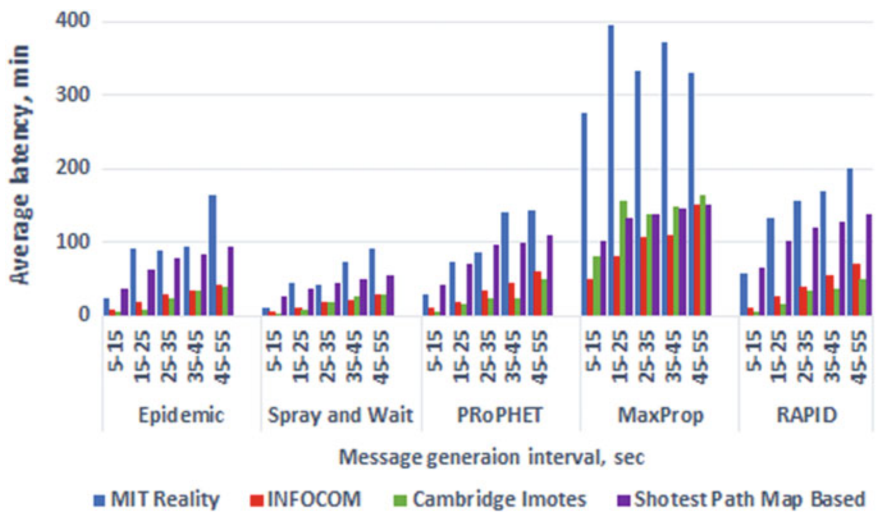

Fig. 4 Average latency versus message generation interval

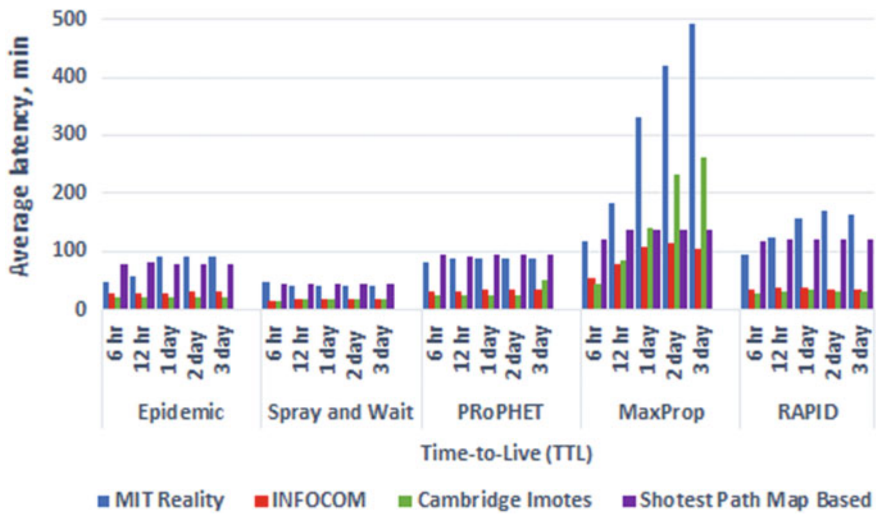

Fig. 5 Average latency versus TTL

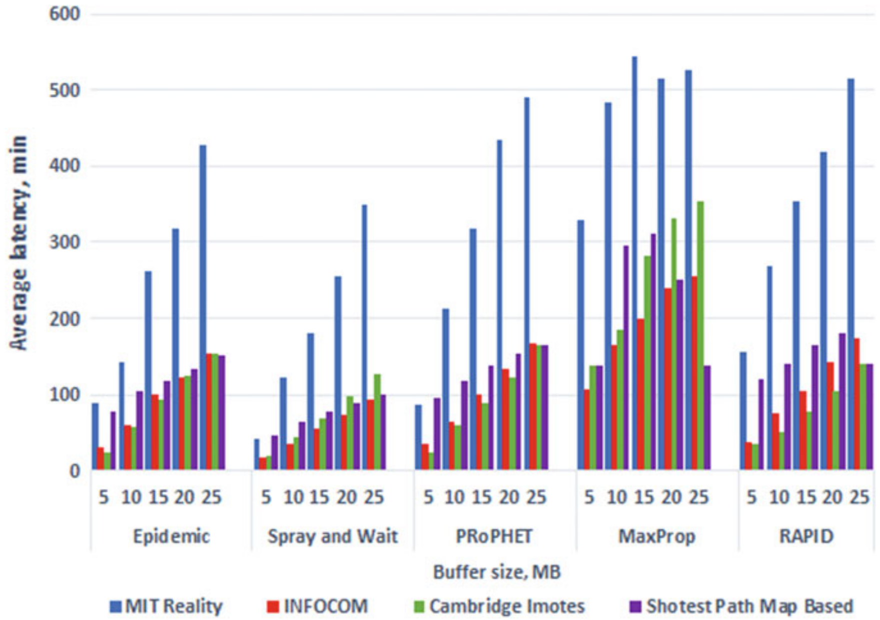

Fig. 6 Average latency versus buffer size

size (5 MB) are fixed, as in Fig. 5. So, it is the worst-performing routing protocol in this case. Furthermore, Spray and Wait protocol on Cambridge Imotes is the best performer in terms of average latency with variation in TTL.

From Fig. 6, it is observed that MIT Reality on MaxProp protocol has the highest latency value with increasing buffer size from 5 to 25 MB. So, it is the worst-performing protocol for the average latency metric. The Spray and Wait protocol configured with INFOCOM trace is the best performer since it has the lowest latency.

Overhead Ratio: This performance metric measures the transmitting efficiency of a network. It can be defined as the estimation of the number of redundant packets that are to be relayed to deliver a single data packet and are supposed to be minimum. Figures 7, 8 and 9 depict the impact of overhead ratio for the selected mobility models on the experimented protocols with varying message generation intervals (5–15 s to 45–55 s), TTL (6 h–3 d), and buffer size (5–25 MB).

It can be decided from Fig. 7 that Spray and Wait protocol configured with INFOCOM, Cambridge Imotes, and Shortest Path Map-Based Movement model has the lowest value of the overhead ratio. But among these three, INFOCOM trace has a little lesser value of the overhead ratio (for 35–45 s and 45–55 s). Except that, for other message generation interval values, these three models have the same value. So, it is evident that Spray and Wait protocol on INFOCOM is the best performer in this case. Here, TTL (1 d) and buffer size (5 MB) are maintained fixed as in the earlier. Besides, MIT Reality trace on MaxProp protocol has the highest value of

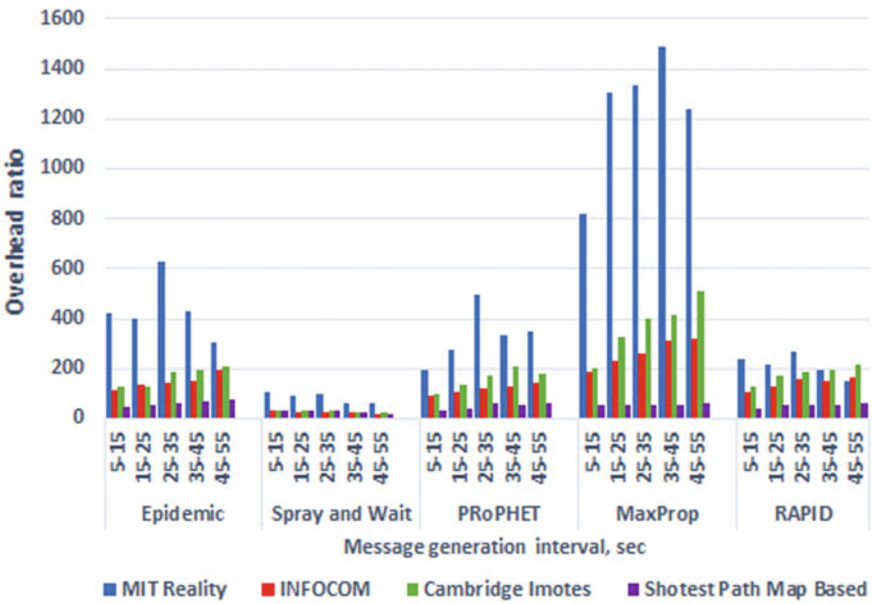

Fig. 7 Overhead ratio versus message generation interval

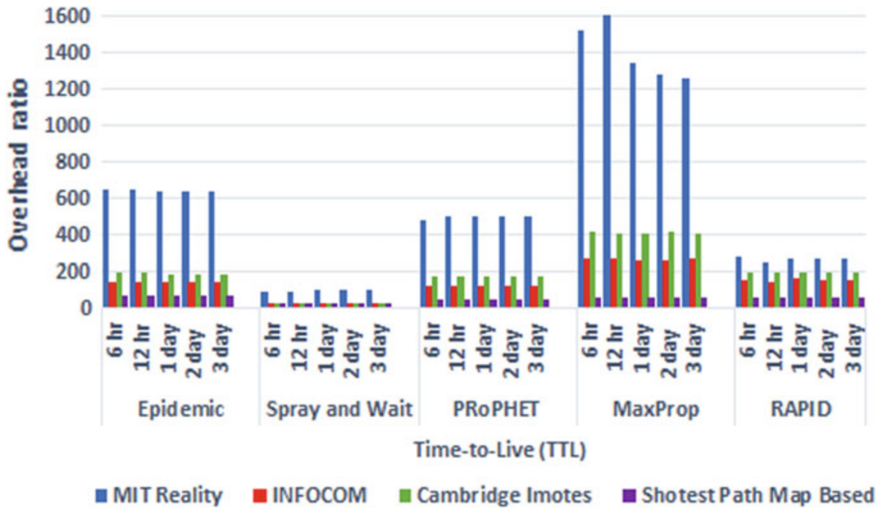

Fig. 8 Overhead ratio versus TTL

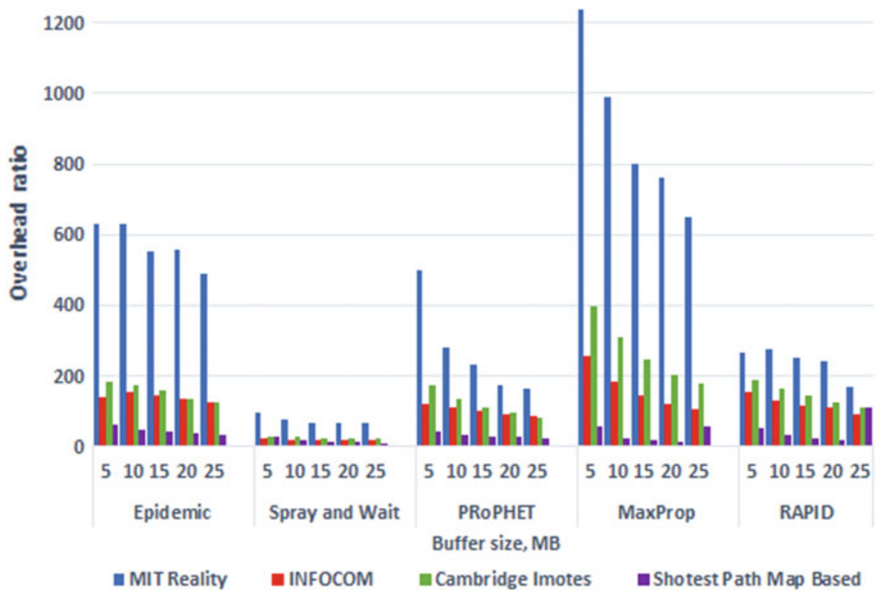

Fig. 9 Overhead ratio versus buffer size

overhead ratio with the increase of message generation interval. So, it is the worst performer in this case.

MIT Reality for MaxProp protocol exploits the maximum overhead ratio in Fig. 8 among the others with the variation of TTL from 6 h to 3 days, while message generation interval (25–35 s) and buffer size (5 MB) are kept constant. On the contrary, it seems that INFOCOM, Cambridge Imotes, and Shortest Path Map-Based Movement Model for Spray and Wait protocol have the lowest overhead ratio values altogether. But among the three mobility models, INFOCOM trace configured with Spray and Wait protocol has the least minimum values of the overhead ratio. So, INFOCOM trace is the best-performing trace on Spray and Wait protocol.

It can be seen from Fig. 9 that the worst performer for the overhead ratio is MIT reality in MaxProp protocol against the change of buffer size. Message generation interval and TTL are preserved at 25–35 s and 1 day, respectively. Contrarily, Shortest Path Map-Based Movement model on Spray and Wait performs the best compared to all since the value of the overhead ratio is the lowest for it in such a case.

7 Conclusions and Future Work

In this research, we have analyzed the impacts of the examined mobility models (three trace-based mobility models and one synthetic mobility model) on the performance of the five DTN routing protocols mentioned above, considering the variations of message generation intervals, TTL, and buffer size in turn. After evaluating all of the simulation outcomes, we conclude that Shortest Path Map-Based Movement model on MaxProp protocol has the highest delivery ratio with the variation of both TTL and buffer size. Furthermore, this synthetic mobility model has the highest delivery ratio for the increasing message generation interval for MaxProp and Spray and Wait protocols. On the other hand, MIT Reality on the Epidemic protocol is the worst performing for delivery ratio with the change of message generation interval, TTL and buffer size, respectively. Besides, MIT Reality on MaxProp protocol shows the worst performance for average latency and overhead ratio with varying message generation interval, TTL and buffer size. In addition, INFOCOM on Spray and Wait protocol for average latency and overhead ratio with varying message generation intervals, Cambridge Imotes on Spray and Wait with varying TTL for average latency, and INFOCOM on Spray and Wait for overhead ratio with varying TTL exhibit the best performance. Furthermore, Spray and Wait on INFOCOM is the best performer for average latency with varying buffer sizes. At the same time, Shortest Path Map-Based Movement on Spray and Wait has the best performance for overhead ratio. The future research endeavor will investigate the impacts of trace-based mobility models on the performance and energy consumption of social-aware DTN routing protocols from different perspectives.

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