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PERFORMANCE EVALUATION OF DTN ROUTING PROTOCOLS ON MAP-BASED SOCIAL MOBILITY MODELS FOR DTN NETWORKS

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ABSTRACT

Delay-tolerant networks (DTNs) are mobile networks that experience frequent and persistent partitions due to high node mobility and sparse distribution of nodes. As well as, the unpredictable and random topology changes and frequent node disconnections encountered in DTNs pose several routing challenges and several challenges to the design of effective DTN routing-protocols. For the majority of DTN routing-protocols, nodes rely on their mobility to forward messages to their destinations. Therefore, it is important to understand the impact of commonly used social mobility models on the performance of DTN routing-protocols already designed for DTN networks. The main objective of this article is the evaluation of the performance of routing-protocols DTN, Epidemic, Prophet, MaxProp and Spray-and-Wait on the three map-based social mobility models, MBM (Map Based Movement), SPMBM (Shortest Path Map Based Movement) and MRM (Map Route Movement), taking into account four performance metrics: Delivery Rate, Average latency, Overhead Ratio and Average hop count. The performance evaluation and the production of realistic traces of the mobility of the nodes is done using the ONE (Opportunistic Network Environment) simulator. The simulation results obtained according to the density of the nodes show that the models of social mobility have a significant effect on the routing process and the performance of DTN routing-protocols.

Keywords: *Delay Tolerant Networks (DTN); Routing Protocol Performance; Epidemic; Prophet; MaxProp; Spray-and-Wait; Social Mobility Models; MBM; SPMBM; MRM; ONE Simulator.*

1. INTRODUCTION

Mobility models play an important role in improving the performance of routing-protocols designed for DTN networks. DTN networks [1] are generally characterized by intermittent connections, persistent disconnections, absence of end-to-end communication paths between a source node and a destination node, unpredictable topology changes, high error rates, long propagation delays between nodes due to mobility and scattered deployment of nodes. However, the connectivity of DTN networks as well as the performance of routing-protocols can be improved by exploiting node mobility. Recently, many research works have been done to enable communication between mobile nodes and improve routing in DTN networks with intermittent connections by exploiting node mobility. Among the research works that have been proposed to improve routing in DTN networks by exploiting the mobility of nodes, we can cite:

- In [2], researchers adopt a strategy based on the mobile similarities and the social similarities of the nodes in the DTN networks. This strategy uses the node mobility history and the social attributes of the nodes (social relations between nodes) and to determine the degrees of similarity between them in order to make good routing decisions.
- The authors in [3] propose the use of special nodes called message ferries adopting a more or less planned mobility model often inspired by real human behaviors to improve connectivity and establish connectivity in a network partitioned into several clusters. The role of these nodes is to collect and transport messages between clusters in the DTN network to improve inter-cluster and intra-cluster routing in DTN networks.
- Researchers in [4][5] propose routing approaches based on the mobility of certain nodes which have high activity in the network

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to improve probabilistic routing in DTN networks by exploiting mobile nodes as common carriers (delegated) of messages between the partitioned network.

The growing interest of researchers in the field of DTN networks and the impact of mobility on the performance of these networks has led to the development of several social mobility models that take into account cartographic mobility, daily activities, mobility based on obstacles and social attractions.

- Map-based social mobility models: Several map-based models of social mobility have been developed using real traces and a synthetic theory that attempts to reach reality. Many map-based social mobility models are still widely used to facilitate the evaluation of DTN routing-protocols. Among them: Map-based Mobility (MBM) [20] is one of the random mobility models where nodes move with speed and directions following a map. Shortest Path Map Based Mobility (SPMBM) [20] is a random mobility model in which nodes select destinations on the map and then travel to those destinations according to Dijkstra's shortest path algorithm. Map Route Mobility (MRM) [20] is a mobility model in which mobile nodes must assign predetermined routes that they must travel on a map.
- Social mobility patterns based on daily activities: The authors in [6] proposed a workday model (WDM) that mimics the daily activities typically performed by humans during a work week, such as going to the office, going home, participating in activities with friends in the evening. Another social mobility model for students is proposed by [7], the mobility model is inspired by the daily life of students. The model distinguishes between free time for students and mandatory time that simulates social and academic activities.
- Social mobility models based on obstacles: The authors of [8] proposed a social mobility model to describe the daily activities of students in the campus environment. The model includes obstacles of various sizes and shapes that hinder the movement and propagation of the signal. Another realistic mobility model proposed by [9]. This model mimics realistic mobility models and uses real-world traces in the presence of obstacles of different sizes and shapes. The model is used to describe several student activities that change regularly over time, such as going to classes, going to coffee, doing hobbies and shopping.
- Mobility models based on attractions and social relations: The authors [10] proposed a mobility model based on the principles of social networks called Community Mobility Model (CMM). This model makes it possible to group collections of nodes according to the social relations between individuals. In this model, nodes depending on the same community represent friendly nodes, while nodes depending on a different community represent non-friendly nodes. Another social-based mobility model called GeSoMo proposed by [11]. This model takes a social network as input. On this basis, the GeSoMo mobility model creates movement trajectories, which are then followed by nodes, and these trajectories create encounters between nodes according to their forces of attraction and their social relations.

Each of the mobility models mentioned earlier provides a different perspective on the behavior of mobile nodes, allowing researchers to assess the performance of DTN routing protocols in various contexts. Map-based social mobility models, in particular, are valued for their ability to incorporate realistic social elements, such as interactions between nodes based on their position on a map, social attraction zones, and other features specific to the real environment. This paper focuses on the in-depth study and performance evaluation of DTN routing protocols in the context of Map-based social mobility models such as MBM, SPMBM, and MRM. It also aims to elucidate the impact of users' social attractions on the efficiency of these routing protocols in DTN networks. This research work is necessary for several important reasons, namely:

- Evaluation of DTN protocols in realistic scenarios: Map-based social mobility models allow scenarios to be simulated closer to reality by integrating social and preference aspects. This is crucial for evaluating how DTN routing protocols behave in environments where mobility is strongly influenced by social factors.
- Optimize the use of DTN routing protocols in varied and complex social mobility contexts to maximize the efficiency of DTN routing protocols in DTN network environments.
- In-depth understanding of DTN protocol behaviors in the contexts of Map-based social mobility models to better guide the choice of the appropriate DTN protocol and social

mobility model based on the specific objectives of DTN applications.

- Design and adaptation of protocols to social mobility contexts: Evaluating DTN protocols on map-based social mobility models is necessary to obtain more realistic simulation results specific to the environments in which DTN networks are deployed. This allows researchers to optimize the use of DTN protocols and design routing protocols that operate effectively under real mobility conditions.

The importance of evaluating the performance of routing protocols on map-based social mobility models lies in their ability to make simulations more faithful to social reality, to understand the behaviors of DTN protocols in the contexts of map-based social mobility models, and enable effective adaptation of protocols to specific social mobility contexts. These aspects are crucial for optimizing the use of DTN protocols and designing adaptive and efficient routing protocols in real contexts for DTN networks.

2. PRELIMINARIES

DTN (Delay-Tolerant-Network) networks [1] are wireless mobile networks, capable of transmitting end-to-end information, even when the network is not permanently connected. DTN networks operate in disconnected mode and they can support the mobility of wireless communication equipment. DTN networks are initially designed to support long delay intermittent connections between communication equipment, and they can operate over very long distances where latency can reach several hours or even days [12]. In DTN networks, communication between nodes generally depends on the mobility patterns of certain nodes [2][5], which determine the reachability between nodes for reliable transmission of information. The figure below illustrates an example of communication between mobile nodes within a DTN network. According to the mobility of the nodes, an intermediate node (relay node) is connected to the source, after a time T∈ [T1, T2], the relay node will be connected to the destination, but not to both at the same time. There is therefore no end-to-end connection between the source node and the destination node.

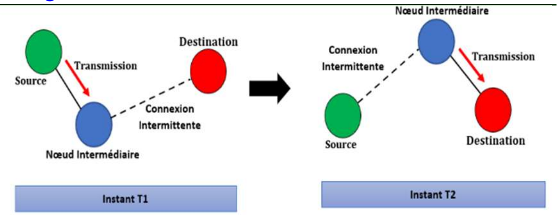

Figure 1: Example of a DTN communication

2.1. Bundle layer

The DTN architecture enables store-and-forward message exchange by superimposing a new protocol layer, called the bundle layer [1] on top of heterogeneous region-specific lower layers. The bundle layer connects region-specific lower layers so that applications can communicate across multiple regions. The figure below illustrates the layering of bundles and compares the Internet protocol layers to the DTN protocol layer. Bundles are also known as messages. The bundle layer stores and transfers entire bundles or bundle fragments between nodes. A single bundle layer protocol is used across all regions (zones) that make up the DTN network. On the other hand, the layers under the bundle layer (transport, network, links and physical) are selected according to the applicability of the communication environment of each area.

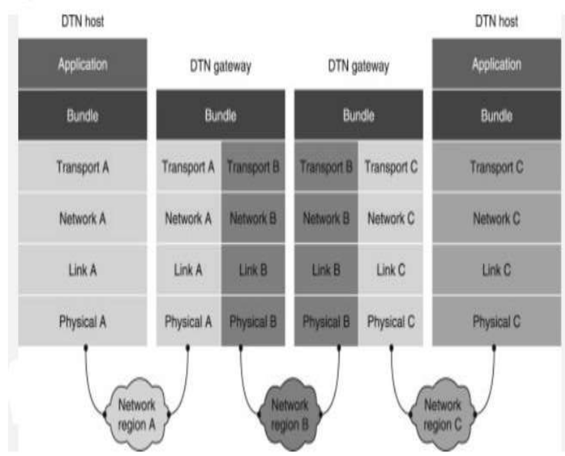

Figure 2: Bundle layer [1]

2.2. Store-Carry and Forward Mechanism

DTN networks can withstand very large and variable transmission delays, very long link disconnection periods, high error rates and also large bidirectional data rate asymmetries. As a result, the DTN network uses a set of routing-protocols based on the "store-carry and forward" mechanism [2] [13] and which make it possible to find an optimal delivery path consisting of a set of intermediate nodes from a source to destination.

This strategy consists of using mobile nodes to put the message in their temporary memories and retransmit it if the opportunity for transmission arises.

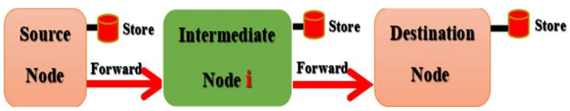

Figure 3: Store-Carry and Forward Mechanism [2]

3. DTN PROTOCOL CHALLENGES AND RESEARCH OBJECTIVES

In DTN networks, routing protocols are closely related to network dynamics, due to the intense mobility of nodes. Thus, mobility plays a determining role in the performance of DTN networks. Mobility exerts a significant influence on communication between nodes in DTN networks because of their displacement that creates new communication links between nodes and interrupt other links. Mobility also affects the routing process in DTN networks and the performance of routing protocols. Indeed, communication paths between the relay nodes leading to the destination are established, while other paths may disappear. On the other hand, humans are the primary carriers of mobile nodes, especially in urban and rural areas. This leads us to evaluate DTN routing protocols in the context of map-based social mobility models, where social attractions, individual node preferences, as well as map data intervene in the routing process. We can summarize the major challenges related to the performance of DTN protocols in the context of map-based social mobility models in DTN networks as follows:

- Intermittent connectivity and variable transmission delays: Map-based social mobility models represent how nodes move along their complex trajectories in the presence of obstacles such as buildings, lakes, etc. This mobility of nodes can lead in intermittent connectivity, where nodes may frequently be out of reach from each other for extended periods of time. This makes it difficult to establish continuous connections, thus imposing constraints on communications and routing.
- Frequent disconnections and limited contact opportunities: Due to the movements of certain nodes in map-based mobility models, disconnections between them are often frequent, and the opportunities for contact between them are often limited. This complicates the direct transmission from one node to another and can cause delays in message transmission.
- Dynamic Topology: Map-based social mobility models influence the network topology by causing dynamic and frequent changes due to the movement of nodes that establish new communication links while interrupting others. This phenomenon impacts the routing process and the performance of DTN protocols.
- Changes in Social Preferences: Some map-based social models use information about individual node preferences, such as preferred locations, preferred routes, etc. These preferences can change over time, which influences the message delivery probabilities and the performance of routing protocols.
- Diversity of map-based social mobility models: Each social mobility model (SPMBM, MBM, MRM) may have distinct characteristics in terms of movement speed, trajectory patterns, social attraction zones, etc. These characteristics directly influence the availability of communication opportunities and can therefore affect the performance of routing protocols.
- Diversity of DTN protocols: Routing protocols can have different strategies depending on the movements of the nodes. Some may favor nearby nodes, while others may rely on strategies more oriented towards opportunistic or probabilistic encounters at longer ranges. The compatibility between these strategies and the characteristics of the social mobility model can influence the performance of DTN protocols.

Consequently, to optimize the use of DTN routing protocols in varied social mobility environments, it is imperative to understand, through in-depth study and rigorous evaluation, the behavior of DTN protocols in the context of map-based social mobility models, where map data and social interactions play a dominant role. This study can lead to the improvement of existing DTN protocols and also to the design of new and more efficient routing strategies in DTN network environments.

4. DTN ROUTING PROTOCOLS USED IN OUR STUDY

4.1. Epidemic Routing Protocol

Epidemic routing [14] [3] is classified among the category of protocols based on flooding and not on knowledge because it does not require any knowledge on the network. Epidemic routing is considered a routing method in dense networks with intermittent connections. Each node uses a "store-carry-and-forward" mechanism to store and broadcast the packets received from the nodes it encounters on its way. Epidemic routing [9] is essentially based on the replication of a sufficient number of copies of a message to relay nodes in the network. A copy of the message is stored until it is delivered to its destination, regardless of latency and storage space.

By analogy, epidemic routing is considered as the propagation of a disease in the network using the maximum of resources, each node of a DTN network infects the other nodes by transmitting a copy of its messages. The following figure shows an example of epidemic routing.

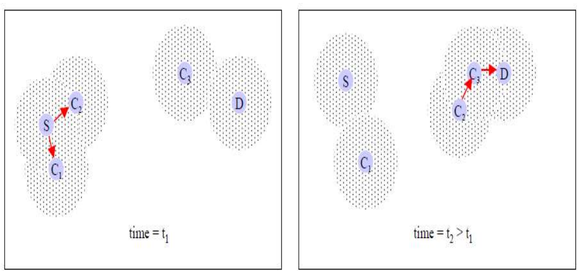

Figure 4: Epidemic routing [14]

4.2. Prophet Routing Protocol

Prophet routing protocol (Probabilistic-Routing-Protocol-using-History-of-Encounters-and-Transitivity) [15][3], is a probabilistic routing protocol that uses the encounter history of mobile nodes (and transitivity) to calculate the probability of delivery (Delivery Predictability) which indicates the probability that a message arrived at the destination via a given intermediate node (transitivity). PROPHET shares summary vectors that contain the probabilities of all nodes to allow other nodes to update their delivery probabilities. The calculation of the probability of delivery is done in three main parts:

- The first part is to update the metric each time a node is encountered, so frequently encountered nodes often have a high delivery probability. This calculation is illustrated in Equation 1, where P(A,B) is the probability that node A encounters node B and Pinit is a constant which is the initial probability that all nodes encounter each other for the first time, which depends a priori on the mobility of the nodes.

$$P(A,B) = P(A,B)_{old} + (1 - P(A,B)_{old}) * P_{init} \quad (1)$$

- The second part, the probability of delivery is also transitive, and equation (2) shows how this transitivity affects the predictability of delivery, According to (2), if A encounters B very frequently, and if B has a very high probability of C (another node C known by B), then A has a very high probability of C with β (0<β<1) being a constant allowing to define the influence of transitivity.

$$P(A,C) = P(A,C)_{old} + (1 - P(A,C)_{old}) * P(A,B) * P(B,C) * \beta \quad (2)$$

- The third part: Equation (3) is calculated for each time period k and helps to reduce the delivery probability of nodes that are not frequently encountered by A. With γ (0<γ<1) defines the value by which the predictability must decrease per unit time. In practice, this value depends on the mobility and the density of the nodes. k is the time elapsed since the last update of P(A,B).

$$P(A,B) = P(A,B)_{old} * \Upsilon^{k} \quad (3)$$

4.3. MaxProP routing protocol

MaxProP [16][3] is a routing protocol designed for DTN networks based on forwarding and on several mechanisms to optimize two routing metrics, the message delivery rate and the average latency (delivery delay). MaxProP defines the order in which the messages are transmitted by referring to the priorities associated with the different messages, knowing that the priority of each message corresponds to the cost associated with its destination. The messages with the highest priority will be transmitted first, and in the event of congestion of the storage unit of the DTN node concerned, the messages that are not prioritized (messages that have the lowest priority) are the most likely to be chosen for deletion first. MaxProp sends messages to other nodes in a specific order that takes into account message hops and message delivery probabilities based on previous encounters. In computational terms, MaxProP estimates probability f (i, j) as the probability that j will be the next node to make contact with node i. For all nodes, f(i, j) will be initialized to:

$$f(i,j) = 1/(Card(s) - 1), \text{ pour } i \neq j \quad (4)$$

When node i encounters another node j, it increments f (i, j) by 1 and again normalizes the costs associated with the different nodes according to the following formulas:

$$f(i,j) = [f(i,j)_{old} + 1]/2, \quad (5)$$
if the node encountered = j

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$$f(i,j) = f(i,j)_{old}/2,$$
$$\text{if node encountered} \neq j \quad (6)$$

Knowing that, for all:

$$\sum_{pour\ tous\ les\ j} f(i,j) = 1, pour\ i \neq j \quad (7)$$

The cost of a path comprising nodes i, i+1, ..., d will be the sum of the probabilities that each connection will not be established along a communication path.

$$c(i, i+1, \dots, d) = \sum_{x=i}^{d-1}[1 - (f_{x+1}^{x})]. \quad (8)$$

4.4. Spray-and-Wait Routing Protocol

The spray-and-wait protocol [17][3] retains the same principles as the epidemic protocol, by limiting in advance the number of copies of a message to be broadcast. It is based on message replication. It limits the number of copies of a message propagated in the DTN network. The Spray-and-wait protocol is seen as being composed of two phases: the first phase is called the spray phase and the second phase is called the wait phase. Spray-and-wait sprays the "L" copies of a message on the "L" intermediate nodes (relay nodes) and waits for one of them to meet the destination node. It is a protocol for zero-knowledge routing that helps reduce redundant flooding of messages in DTN networks, which is not the case for epidemic routing.

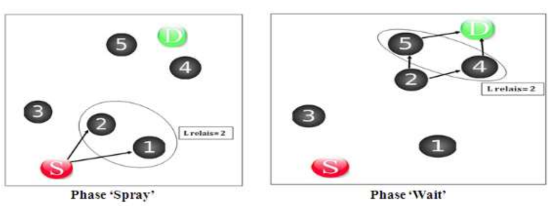

Figure 5: Spray-and-Waite Routing [3]

5. MAP-BASED SOCIAL MOBILITY MODELS USED IN OUR STUDY

In map-based social mobility models, mobile nodes represent mobile devices worn by humans and/or carried by vehicles. Mobility patterns therefore depend on human or vehicle movement, which is often influenced by the social behavior of humans. Many map-based social mobility models have been proposed in recent years by the researchers. Some of these mobility models are often used to evaluate routing-protocols against human behaviors. Broadly speaking, map-based social mobility models can be divided into three models:

5.1. Map Based Movement (MBM)

The Map-Based Social Mobility Model (MBM)[20][21] is a random mobility model inspired by the Random Walk mobility model. Indeed, the movement of mobile nodes in the MBM model is randomly defined by directions and routes on the map which are in fact cartographic data. The MBM mobility model consists of several mobility sub-models that use only a few parts of the map. The mobility sub-models are used to distinguish between the mobility of pedestrians, vehicles (cars, trams, etc.) and other categories of mobile nodes. Indeed, the mobility sub-model prevents vehicles from driving on sidewalks or buildings and also prevents pedestrians from crossing roads. As such, pedestrian nodes are limited to crosswalks, sidewalks, and streets designed for pedestrians. Vehicle nodes are limited to roads which are often separated by buildings, trees and other objects used by roads. In road intersections or the end of a road, mobile nodes randomly choose a new direction and a new route on the map.

5.2. Shortest Path Map Based Movement (SPMBM)

The Shortest Path Based Map Mobility Model (SPMBM) [20][21] is a completely random mobility model. In this model the nodes choose random places (Random Points) in the map area, then the nodes travel to these places on the map according to Dijkstra's shortest path algorithm [18]. In effect, nodes use Dijkstra's algorithm to calculate the shortest path from the current location to a randomly selected destination. The SPMBM mobility model forces mobile nodes to move until they reach their destinations in map areas, just before having to change orientation after a possible pause time. Once the pause time is over, the nodes again randomly choose another destination and repeat the same process. All locations on the map generally have the same chance of being selected as the next destination, however, some areas on the map may also contain popular locations such as Historical Monuments, tourist areas, supermarkets or hotels [19]. These popular locations are called Points of Interest (POI) and have a high chance of being selected as destinations. These POIs are grouped into several POI groups. Each group of nodes can have a configurable probability of choosing a point of interest as the next destination.

5.3. Map Route Movement (MRM)

The Map-Route-Movement (MRM) mobility model [20][21] is a cartographic mobility

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model frequently used to simulate patterns of moving node movement in routes defined by maps. In this model, nodes must assign predetermined routes that they must travel on a map to reach a destination. The next destination is selected by the mobile nodes on their current travel route. This model can be used to simulate the movement of nodes on routes defined by map data and in particular bus and tram lines. A route on a map consists of a set of stops. Nodes must wait a certain amount of time at each stop before moving on to the next stop. This model is generally used to simulate the movement of mobile nodes on routes similar to those used by real road traffic or car traffic on roads defined by real road map data.

6. SIMULATION

In this article, we evaluate the performance of routing-protocols, Epidemic, PRoPHET, MaxProp and Spray-and-Wait designed for DTN networks on the card-based social mobility models,MBM, SPMBM and MRM . The performance of the routing-protocols was evaluated using the ONE (Opportunistic Network Environment) simulator with the program version is 1.6.0.

6.1. ONE Simulation Environment

The ONE simulator [20][21] (Opportunistic Network Environment) was developed to evaluate routing and routing-protocols specific to DTN networks. It allows users to create scenarios based on multiple mobility models based on real-world traces. The ONE simulator includes several routing-protocols designed for DTN networks such as: Epidemic, PRoPHET, MaxProp , Spray-and-Wait, etc, and supports different map-based social mobility models such as: Map-Based Mobility Model (MBM), Shortest Path Map Based Mobility Model (SPMBM), Map Route-Based Mobility Model (MRM) as well as, the ONE simulator provides a framework for improving and implementing new routing-protocols and new models of mobility. The ONE simulator is considered an agent-based discrete-event simulation engine. At each engine simulation step, some modules that perform the main simulation functions will be updated. The main functions of the ONE simulator are: modeling the movement of nodes, inter-node contact using various interfaces, routing using routing-protocols, message processing and interaction with other applications. The collection and analysis of results are carried out using interactive visualization tools, reports and post-processing tools. The elements and their interactions are shown in the figure below:

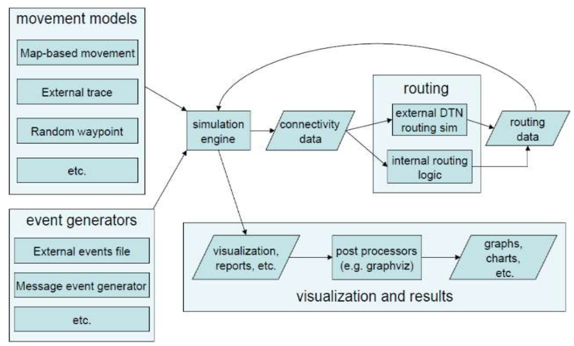

Figure 6: ONE simulation environment [20]

6.2. Performance metrics

In this section, we evaluate the performance of routing-protocols DTN, Epidemic, Prophet, Maxprop and Spray-And-Wait on three social mobility models MBM, SPMBM and MRM, and consider four performance metrics, namely: Average_latency, Overhead_ratio, Delivery_rate and Average_hop_count

7.1.1. Delivery rate

The delivery rate is the ratio between the number of messages successfully received by the destination node and the number of messages created by the source node. The delivery rate is the most important metric in the routing process, it helps to evaluate the routing efficiency in DTN networks. For better network performance, this metric should be high

7.1.2. Average latency

Average latency is the time elapsed between the creation of a message by the source and its successful delivery to the destination. For best network performance, this setting should be lower.

7.1.3. Overhead ratio

Overhead rate is number of replications of a message required for successful delivery. In other words, it is the transmission cost in the network. Overhead Rate is used to gauge bandwidth efficiency.

7.1.4. Average hop count

This is the number of nodes a message must pass through to travel from source to destination. This allows us to know the resources used and consumed in the network when the

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messages are transmitted from the source to the destination.

6.3. Simulation parameters and setting

We have adopted the default configuration of version 1.6.0 of the ONE simulator. All locations on the map as well as points of interest (POIs) generally have the same chance of being selected by nodes as destinations. For the simulation area, we used a part of the city of Helsinki with dimensions (4500×3400 m), as shown in the map of Helsinki below [20].

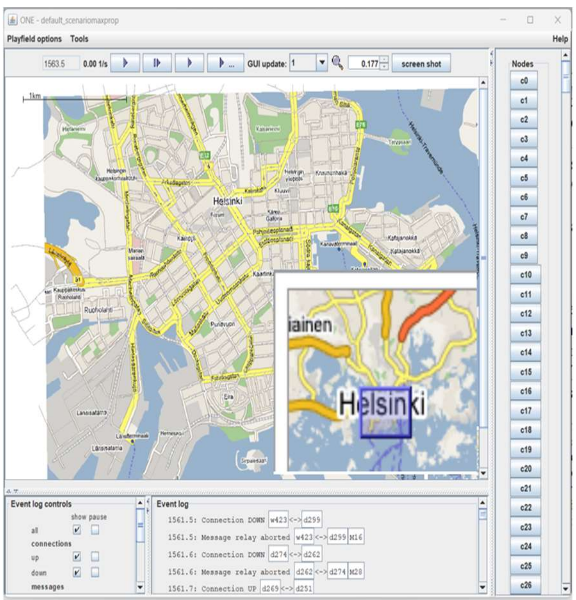

Figure 7: Helsinki map simulation area [20]

Table 1 shows the simulation parameters used to evaluate the performance of various DTN routing-protocols on the three social mobility models, MBM, SPMBM and MRM in the ONE simulation environment.

Table 1: simulation parameters

Parameter	Value
Total Simulation Time	12h
Simulation area	Helsinki Map
World Size	4500 X 3400 m2
Points of Interest (POIs)	Park, Central, West, shops
DTN Routing Protocol	Epidemic, Prophet, MaxProp et Spray- and -Wait (L=6).
Social Mobility models	MBM, SPMBM et MRM
Buffer Size	5M
Total No. of nodes	50, 75, 100, 125, 150.
Types of nodes	Pedestrians, Cars, Trams
Pedestrians speed	Min=0.5 m/s Max=1.5 m/s
Cars speed	Min=2.7m/s Max=13.9m/s
Trams speed	Min=7m/s Max=10m/s
Pedestrians wait Time	0–120 s
Cars wait Time	0–120 s
Trams wait Time	10–30 s
Seconds in time unit	30s
No. of copies (L)	6
Transmit Speed	2 Mbps
Message TTL	300 minutes
Interface Transmit Range	10 metres
Message Creation Rate	A message by 25-35 sec
Message Size	50 KB to 150 KB

7. RESULTS AND DISCUSSION

In the ONE simulation environment, we evaluate the performance of routing-protocols DTN, Epidemic, Prophet, MaxProp and Spray-and-Wait on the three social mobility models MBM, SPMBM and MRM taking into account four performance metrics namely: Average_latency, Delivery_Rate, Overhead_Ratio, Average_hop_count.

7.1. Performance Evaluation on Delivery rate

The figures below show the delivery rate of the routing-protocols DTN: Prophet, Epidemic, Spray-and-Wait and MaxProp evaluated on the three social mobility models: SPMBM, MBM and MRM, by varying the number of nodes.

7.1.1. Delivery rate of evaluated DTN protocols on MBM

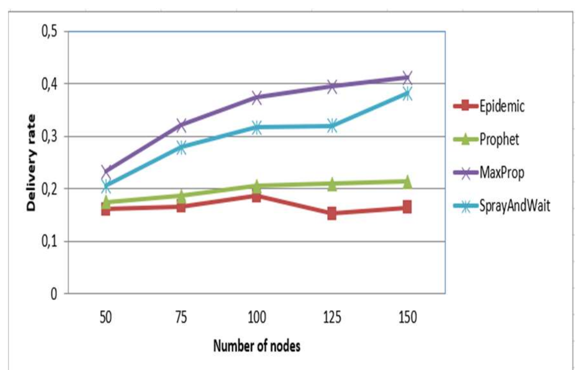

Figure 8: Delivery rate of evaluated DTN protocols on MBM

Figure 8 shows the Delivery Rate of DTN Routing-Protocols evaluated on the MBM Social Mobility Model. According to figure 8, the probability of delivery increases with the increase in number of nodes for the Maxprop and spray-and-Wait protocols, however the Epidemic and Prophet protocols show a low and almost constant probability of delivery with any increase in the number of nodes. In particular, the Maxprop and Spray-and-Wait routing protocol have average

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delivery rates that exceed 0.41 for the Maxprop protocol and 0.38 for the Spray-and-Wait protocol. On the other hand, the Prophet and Epidemic routing-protocols present a low and almost constant delivery rate which does not exceed 0.21 for the Prophet protocol and 0. 16 for the Epidemic protocol. These results are justified by the use of the MBM mobility model by the nodes.

7.1.2. Delivery rate of evaluated DTN protocols on SPMBM

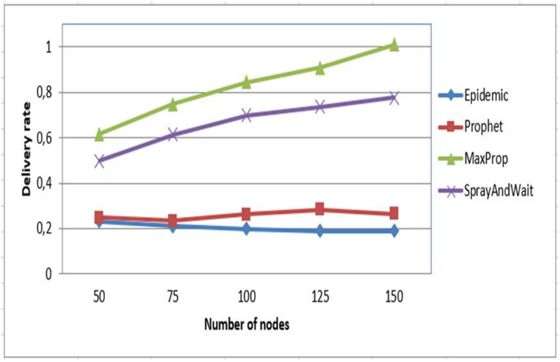

Figure 9:Delivery rate of evaluated DTN protocols on SPMBM

Figure 9 shows the delivery rate of DTN protocols evaluated on the SPMBM model. According to Figure 9, the delivery rates of the Maxprop and Spray-and-Wait protocols increase as the number of nodes increases, but the Epidemic and Prophet protocols show that the delivery rates are nearly constant as the number of nodes increases. The Maxprop protocol has a delivery rate of 0.99 and the Spray-and-Wait protocol has a delivery rate of 0.77. On the other hand, the Prophet and Epededic routing-protocols show low and almost constant delivery rates that do not exceed 0.26 for the Prophet protocol and 0.19 for the Epidemic protocol. These results can be explained by the use of the SPMBM mobility model. Indeed, the Maxprop and spray-and-wait routing-protocols are the best performing in terms of delivery rate compared to the Epidemic and Prophet routing-protocols.

7.1.3. Delivery rate of evaluated DTN protocols on MRM

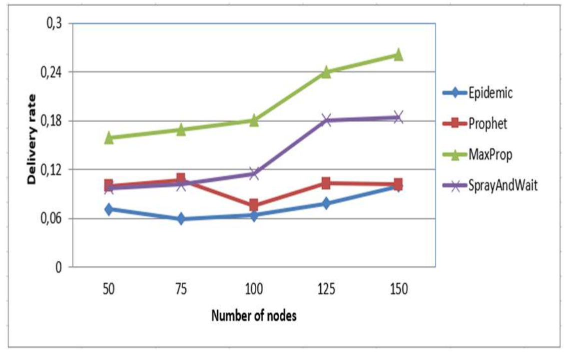

Figure 10. Delivery rate of evaluated DTN protocols on MRM

Figure 10 shows the delivery rate of DTN routing-protocols evaluated on the MRM social mobility model. According to Figure 10, for the Maxprop and Spray-and-Wait protocols, the probability of delivery increases with increasing node density, but the Epidemic and Prophet protocols show a low and almost constant delivery rate with any change in the node density. In fact, Maxprop and Spray-and-Wait routing-protocols have high delivery rates compared to other protocols, this probability exceeds 0.26 for Maxprop protocol and 0.18 for Spray-and-Wait protocol. On the other hand, the delivery rates of the Prophet and Epidemic routing-protocols are very low and do not exceed 0.1 for the Prophet protocol and 0.09 for the Epidemic protocol. These results can be explained by the MRM mobility model used by the nodes.

7.1.4. Synthesis of evaluations

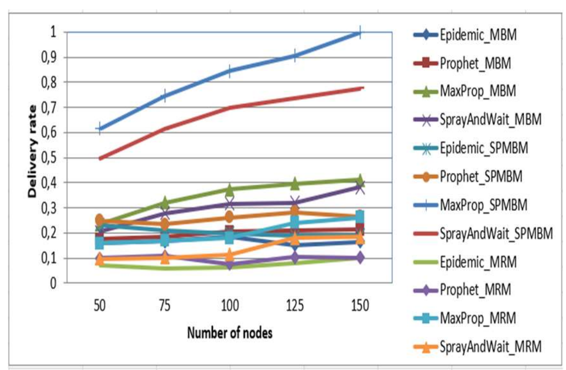

Figure 11: Delivery rate of evaluated DTN protocols on MRM, SPMBM et MRM

The delivery rates obtained for the different routing-protocols evaluated on the three social mobility models are illustrated in Figure 11. According to Figure 11:

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- For the three social mobility models, the delivery rate of the Maxprop and spray-and-Wait protocols increases with increasing number of nodes, however the delivery rate is low and almost constant for the Epidemic and Prophet protocols.
- Maxprop and Spray-and-Wait protocols provide very good performance in terms of delivery rate compared to Epidemic and Prophet protocols provide low and poor delivery rate for all three mobility models.
- Routing-protocols provide a maximum delivery rate for the SPMBM mobility model followed by the MBM mobility model however they provide a minimum and poor delivery rate for the MRM model.

These results can be justified as follows:

- **SPMBM:** In the SPMBM model, nodes follow the shortest path on a map to reach their destination. This predictability can allow Maxprop and Spay-and-Wait routing protocols to schedule more efficient message transfers along the shortest paths. Optimized transmission opportunities over shortest paths can lead to very high delivery rates, because Maxprop and Spay-and-Wait protocols exploit the predictable structure of movement to minimize delays and increase the chance of successful transmissions.
- **MBM:** In the MBM model, where nodes move according to a predefined map, the mobility prediction may be less accurate than in the SPMBM model. Paths may be less direct, leading to less predictable encounter opportunities. This can result in average performance in terms of delivery rates, as DTN protocols and especially Epidemic and Prophet protocols, struggle to effectively anticipate transmission opportunities in a less predictable mobility environment.
- **MRM:** In the MRM model, where nodes follow specific routes on the map, the predictability of encounters between nodes is reduced. Specific routes may not match the shortest paths, and transmission opportunities are less efficient. DTN protocols and in particular the Epidemic protocol have more difficulty anticipating encounter opportunities along specific routes, resulting in poor performance in terms of delivery rates. The predefined routes may not be optimal for facilitating efficient message delivery.

7.2. Performance Evaluation on Average Latency

The figures below show the average latency of the DTN routing-protocols: Epidemic, MaxProp, Prophet and Spray-and-Wait evaluated on the three social mobility models: MBM, SPMBM and MRM, by varying the number of nodes.

7.2.1. Average latency of evaluated DTN protocols on MBM

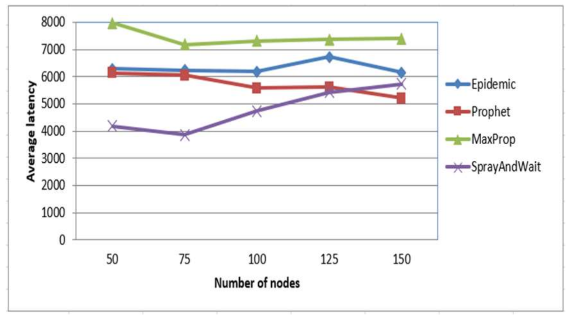

Figure 12: Average latency of evaluated DTN protocols on MBM

Figure 12 shows the average latency as a function of number of nodes. According to figure 12, the average latency is quite large for the four DTN protocols, it is bounded between 4000 and 8000 and this because of the MBM social mobility model used by the mobile nodes. In the case of the MBM social mobility model, the average latency is lower for Maxprop and Prophet protocols compared to other routing-protocols.

7.2.2. Average latency of evaluated DTN protocols on SPMBM

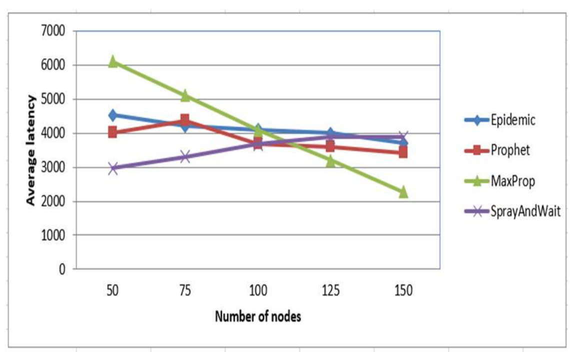

Figure 13: Average latency of evaluated DTN protocols on SPMBM

In Figure 13, the average latency is medium for the DTN protocols that are the subject of this study, it is bounded between 2000 and 6000 and this because of the SPMBM model used by the

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nodes. In particular, the average latency of the Maxprop protocol is decreased with increasing node density. Indeed, we find that the MaxProp routing protocol is the most powerful among the four routing-protocols evaluated on the SPMBM model.

7.2.3. Average latency of evaluated DTN protocols on MRM

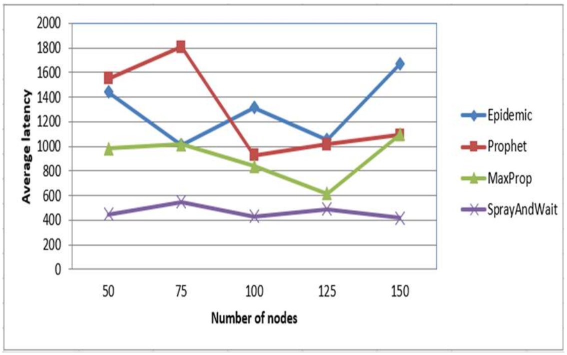

Figure 14: Average latency of evaluated DTN protocols on MRM

Figure 14 shows that the average latency is low for the four DTN protocols evaluated on the MRM model. The average latencies of the four protocols are bounded between 400 and 1800 and this due to the MRM model used by the nodes. In particular, the average latency is lower for the Spray-and-Wait protocol compared to the Prophet, Epidemic and Maxprop routing-protocols. We find that the Spray-and-Wait protocol performs best in terms of average latency compared to other routing-protocols evaluated on the MRM model.

7.2.4. Synthesis of evaluations

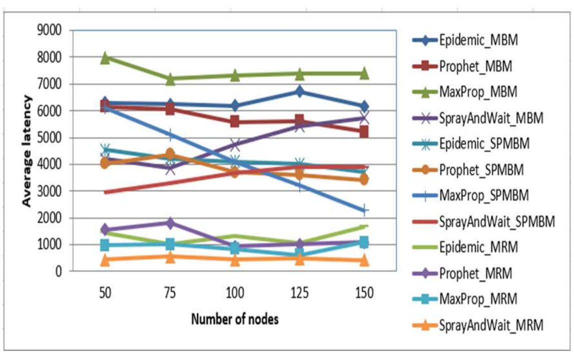

Figure 15. Average latency of evaluated DTN protocols on MBM, SPMBM et MRM

The average latencies obtained for the different routing-protocols evaluated on the three mobility models are shown in Figure 15. According to Figure 15:

- The four routing-protocols provide very good average latency for the MRM model, followed by the SPMBM model, however it provides poor average latency for the MBM model.
- For the three social mobility models, we find that the Spray-and-Wait protocol performs best in terms of average latency for the MRM model, and the MaxProp protocol performs best for the SPMBM model, Maxprop and Prophet protocols are the best performers for the MBM model.

These results can be interpreted as follows:

- **Spray-and-Wait with the MRM model**: The MRM model assumes that nodes follow specific routes on the map. Spray-and-Wait is particularly effective in this context due to its spray transmission strategy, which allows copies of messages to be broadcast over different possible routes. This can compensate for the specificity of routes in the MRM model, thereby improving the chances of message delivery and potentially reducing average latency.
- **MaxProp with SPMBM model**: The SPMBM model assumes that nodes follow the shortest path on a map to reach their destination. MaxProp performs well in this context by exploiting knowledge of the shortest path to make optimal routing decisions. This can reduce average latency by favoring more direct and efficient paths for message transfers.
- **Spray-and-Wait and Prophet with the MBM model**: The MBM model assumes that nodes move according to a predefined map. Spray-and-Wait, with its spray transmission strategy, can perform well in this context by exploiting encounter opportunities between nodes. Prophet, relying on historical predictions, can also adapt to mobility patterns defined by the map, allowing better anticipation of data transfer opportunities.

7.3. Performance Evaluation on Overhead Ratio

The figures below show the Overhead Rate of the four DTN routing-protocols: Epidemic., Prophet, MaxProp, and Spray-and-Wait evaluated on the three social mobility models: MBM, SPMBM, and MRM, by varying the number of nodes.

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7.3.1. Overhead Ratio of evaluated DTN protocols on MBM

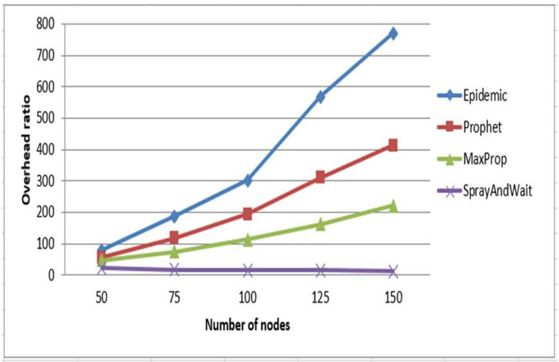

Figure 16: Overhead Ratio of evaluated DTN protocols on MBM

The Overhead Ratio depends on the number of replications of a message and the transmission cost required for successful delivery for each DTN protocol. According to Figure 16, the Overhead Ratio of the four DTN protocols is low, it is bounded between 12 and 770, due to the MBM mobility model used by the nodes. According to Figure 16, the Spray-ans-Wait protocol is the most efficient, followed by the MaxProp protocol, while the Epidemic and Prophet protocols have higher Overhead Ratio values and in particular the Epidemic protocol which shows a very large Overhead Ratio. This result is due to the high number of replications that characterizes the epidemic protocol.

7.3.2. Overhead Ratio of evaluated DTN protocols on SPMBM

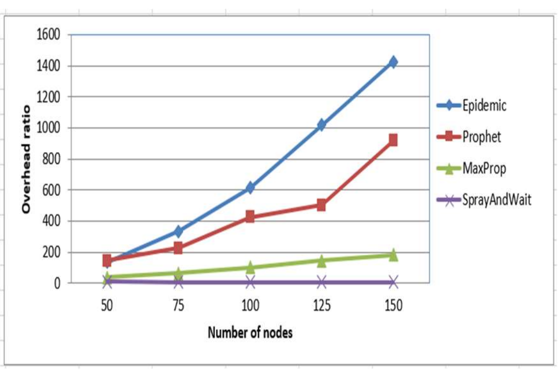

Figure 17: Overhead Ratio of evaluated DTN protocols on SPMBM

According to Figure 17, the Overhead Ratio of the four DTN protocols evaluated on the SPMBM mobility model is average, it is bounded between 6 and 1400. These average values are justified by the SPMBM mobility model used by the nodes. As shown in Figure 17, with the increase in the number of nodes, the Overhead Ratio increases for all protocols except the Spay-and-Wait protocol where the Overhead Ratio is low and it gradually decreases. Therefore, the Spray-and-Wait protocol is the best performer and the epidemic protocol is the worst performer compared to the other protocols in terms of overhead ratio.

7.3.3. Overhead Ratio of evaluated DTN protocols on MRM

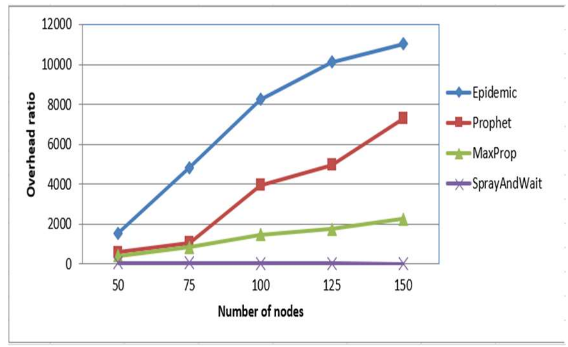

Figure 18: Overhead Ratio of evaluated DTN protocols on MRM

As shown in Figure 18, the Overhead Ratio provided by the four DTN protocols evaluated on the MRM mobility model is important and it is bounded between 26 and 11019. These large Overhead Ratio values are mainly due to the MRM mobility model used by the different mobile nodes. In Figure 18, as the number of nodes increases, the Overhead Ratio of all protocols increases, except the Spay-and-Wait protocol, which gradually decreases. Therefore, in terms of Overhead Ratio, the Spray-and-Wait protocol performs the best compared to the other protocols and the Epidemic protocol performs the worst.

7.3.4. Synthesis of evaluations

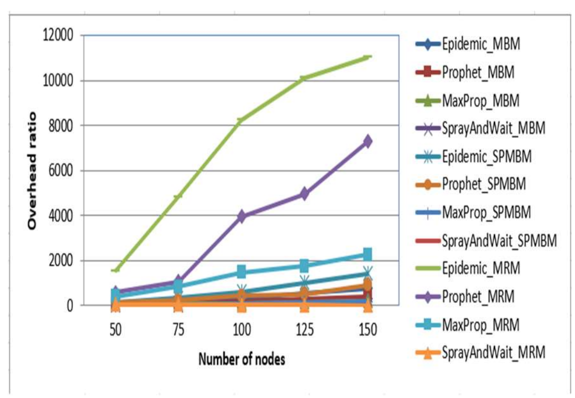

Figure 19: Overhead Ratio of evaluated DTN protocols on MBM, SPMBM et MRM

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Figure 19 illustrates the Overhead-Ratio obtained for the different routing-protocols evaluated on the three social mobility models. According to Figure 19:

- The overhead-ratio provided by the Spray-and-Wait protocol decreases progressively with increasing number of nodes, however the overhead-ratio provided by the Epidemic, Maxprop and Prophet protocols increases with increasing number of nodes.
- For the three mobility models, the spray-and-wait protocol is the best performing in terms of the Overhead-Ratio, however the epidemic protocol is the least performing compared to the four DTN protocols evaluated on the three social mobility models.
- Routing-protocols provide very good performance for the SPMBM mobility model, and they provide average performance for the MBM model, however, they provide poor performance for the MRM model.

These results can be justified as follows:

- **SPMBM:** In the SPMBM model, where nodes follow the shortest path on a map to reach their destination, the Spray-and-Wait protocol benefits from the predictability of movements. The shortest paths provide more efficient transmission opportunities. The Spray-and-Wait protocol uses a spray transmission strategy that aims to minimize the number of copies of a message by replicating a limited number of messages. This strategy minimizes the Overhead Ratio compared to epidemic, Prophet, and Maxprop protocols.
- **MBM:** In the MBM model, less accurate mobility prediction and less direct trajectories of nodes lead to less predictable encounter opportunities. This can result in additional overhead because the DTN protocols and especially the Epidemic, Prophet, and Maxpop protocols, generate more message copies to compensate for less predictable mobility, which results in average performance in terms of Overhead Ratio.
- **MRM:** In the MRM model, predefined routes on a map introduce a certain rigidity in node movements and may not always favor frequent encounters between nodes. The Prophet and Maxprop protocols have more difficulty anticipating encounter opportunities, leading to an increase in the Overhead Ratio. The epidemic protocol tends to propagate copies to all nodes encountered, which can result in high overhead.

7.4. Performance Evaluation on Average hop count

The figures below show the average hop count of the four DTN routing-protocols: Epidemic, Prophet, MaxProp and Spray-and-Wait evaluated on the three social mobility models: MBM, SPMBM and MRM, by varying the number of nodes.

7.4.1. Average hop count of evaluated DTN protocols on MBM

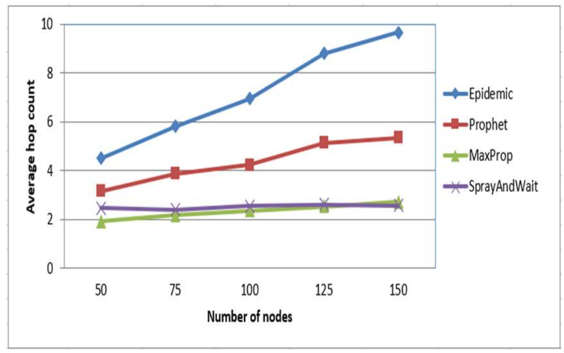

Figure 20: Average hop count of evaluated DTN protocols on MBM

The average hop count is an important metric for interpreting and evaluating the performance of DTN routing-protocols. According to Figure 20, The average hop count of the four DTN protocols evaluated on the MBM mobility model is bounded between 1.9 and 9.6. These results are justified by the MBM mobility model used by mobile nodes. From Figure 20, it is clear that the Spray-and-Wait and Maxprop routing-protocols have a minimal number of hop counts compared to the Prophet and Epidemic protocols. The average hop count increases with the increase in the number of nodes for all protocols except the Spay-and-Wait protocol where the average hop count is constant and almost identical.

7.4.2. Average hop count of evaluated DTN protocols on SPMBM

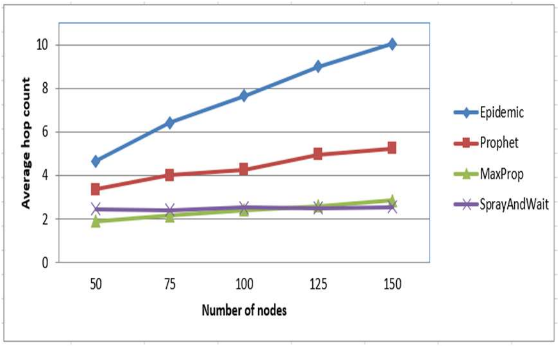

Figure 21: Average hop count of evaluated DTN protocols on SPMBM

The routing-protocols provide almost the same results in terms of average hop count for the MBM and SPMBM social mobility models. From Figure 21, the Spray-and-Wait and Maxprop routing-protocols have the fewest hops compared to the Prophet and Epidemic protocols. For all protocols, the average hop count increases with the number of nodes, except for the Spay-and-Wait protocol, where the average hop count is constant and almost the same.

7.4.3. Average hop count of evaluated DTN protocols on MRM

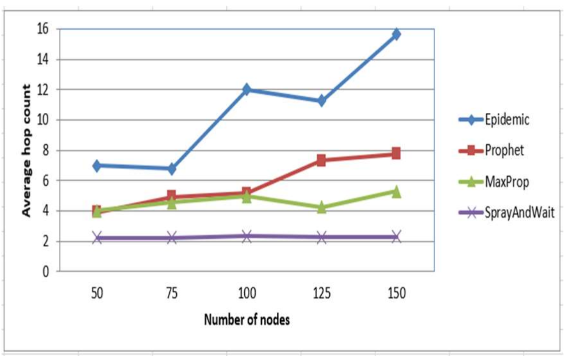

Figure 22: Average hop count of evaluated DTN protocols on MRM

According to Figure 22, The average hop count of the four DTN protocols evaluated on the MRM mobility model is bounded 1.9 and 9.6. These results are justified by the MRM mobility model used by mobile nodes. The Spray-and-Wait and Maxprop routing-protocols have the least hops compared to other protocols. As shown in Figure 22, with increasing number of nodes, the average hop count increases for all protocols except the Spay-and-Wait protocol where the average hop count is low and nearly constant.

7.4.4. Synthesis of evaluations

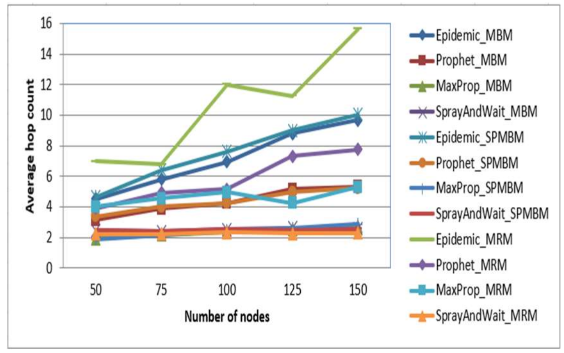

Figure 23: Average hop count of evaluated DTN protocols on MRM, SPMBM et MRM

Figure 23 illustrates the average hop count obtained for the different routing-protocols evaluated on the three social mobility models: MBM, SPMBM and MRM. According to figure 23:

- The Spray-and-Wait and Maxprop routing-protocols have a minimal number of hop counts compared to the Prophet and Epidemic protocols for all three social mobility models.
- The average hop count increases with increasing node density for all protocols except the Spay-and-Wait protocol which provides an almost identical low average-hop-count for all three mobility models.
- For the three mobility models, the spray-and-wait protocol is the best performing in terms of average-hop-count, however the epidemic protocol is the least performing compared to the other protocols.
- Routing-protocols provide very good performance for the SPMBM mobility model, followed by the MBM model, however they provide mediocre performance for the MRM model.

These results can be interpreted as follows:

- **SPMBM:** The SPMBM social mobility model is designed to favor optimal trajectories by using the shortest path between the node's current location and its destination on the map. Spray-and-wait protocol exploit this predictability to choose more direct paths, which reduces the total number of hops required for message transmission. Transmission opportunities along the shortest paths allow the Average Hop Count to be optimized, leading to very good performance.
- **MBM:** In the MBM model, the mobility prediction is less accurate due to the less direct trajectories of the nodes. This forces nodes to

make a greater number of hops to reach their destination, resulting in a higher average hop count for the Epidemic, Prophet, and Maxprop protocols.

- **MRM:** In the context of the MRM model, where specific routes are followed, encounter opportunities may be less predictable, which may make it more difficult for DTN protocols and especially the epidemic protocol to anticipate transmission opportunities along these routes. This could result in a higher average number of hops to reach the destination, as messages may require more relays to follow specific routes rather than shortest paths.

8. COMPARATIVE ANALYSIS WITH OTHER RESEARCH

In our research work, we tackled the performance evaluation of DTN routing protocols in the context of map-based social mobility models by taking into account several different social aspects compared to other solutions proposed by researchers. Among the main differences, we can mention:

8.1. Consideration of node diversity and heterogeneous connectivity

- Our solutions: The evaluation of protocols takes into account the diversity of nodes. This includes different types of vehicles, pedestrians, students, etc. The diversity of nodes can also lead to heterogeneous connectivity. Some types of nodes may have faster mobility, while others may be more static. Social mobility is often characterized by heterogeneous movements, and our evaluations reflects this diversity.
- Other solutions: In [8], the authors propose a social mobility model (SSBMM) evaluated using routing protocols designed for MANET-DTN networks. This evaluation was realized by simulating the daily mobility routine, specifically focusing on a unique type of nodes, namely students. This could lead to an under-representation of the diversity of mobility behaviors that might be present in reality. Other node types could have different mobility patterns.

8.2. Consideration of the diversity of obstacles

- Our solutions: Our protocol evaluation addresses different types of obstacles, which is closer to the reality of social mobility environments. By considering a diversity of obstacles such as buildings, roads, etc., our study can have a significant impact in providing a more comprehensive and realistic perspective.

- Other solutions: The model proposed by [8] focuses on specific mobility scenarios and does not take into account the diversity of situations that nodes might face in a DTN network. Indeed, the mobility of the nodes and their behavior are restricted to three specific zones of the simulation: the home, the residential area, and the school. This limitation reduces the number of obstacles and does not accurately reflect the complexity of daily life and social interactions.

8.3. Consideration of the diversity of evaluation metrics

- Our solutions: The diversity of evaluation metrics is taken into account in our evaluation of protocols, especially in the context of social map-based mobility models. Four performance metrics are considered, namely: Delivery Rate, Average latency, Overhead Ratio and Average hop count, this allows a rigorous and efficient evaluation.
- Other solutions: The authors in [10] propose simulation scenarios that focus only on the delivery rate, but do not take into account other performance metrics of network protocols. This can make the validation of simulation results obtained difficult to generalize. Indeed, the absence of diverse performance metrics hinders a comprehensive understanding and effective evaluation of communication protocol performance in environments where mobility is influenced by social factors.

8.4. Consideration of protocol diversity

- Our solutions: We studied and evaluated the behavior of several categories of DTN protocols, such as Epidemic, Prophet, Maxprop, Spray-and-Wait, in environments close to reality, including various types of obstacles such as buildings, roads, etc. After interpreting the results of DTN protocol performance evaluations and simulation results, we find that some DTN protocols, such as Maxprop and Spray-and-Wait, are more effective in environments close to reality, including buildings, roads, and social attraction areas. However, other DTN protocols, such as Prophet and Epidemic, exhibit lower effectiveness.

- Other solutions: The authors in [8][10] propose an evaluation of the impact of a social mobility model on the performance of two routing protocols. This limited diversity in routing protocols and social mobility models may not accurately reflect the diversity of situations that networks may encounter. Therefore, the simulation results may be specific to the particular characteristics of these two protocols and this social mobility model, thereby limiting the generalizability of the conclusions.
- Other solutions: The authors, in [19], propose an evaluation of the performance of DTN protocols on social mobility models. However, this evaluation does not take into account the Maxprop protocol, which is a very efficient protocol in the contexts of social mobility models and in realistic environments. The importance of the MaxProp protocol in the context of social mobility models lies in its flexibility and adaptability, allowing to optimize message routing in environments where movements are influenced by social interactions.

8.5. Considering the diversity of social mobility models

- Our solutions: We evaluated DTN protocols in the context of three map-based social mobility models (SPMBM, MBM, MRM). Each social mobility model has distinct characteristics in terms of movement speed, trajectory patterns, social attraction zones, etc. This diversity of mobility models makes it possible to realistically reflect the performance of routing protocols and the real mobility dynamics present in a DTN network. From the simulation results we observe that DTN protocols have better performance in the context of the SPMBM model, and average performance in the context of the MBM model, however DTN protocols have lower performance in the context of the MRM model. These observations suggest that the specific nature of each map-based social mobility model can significantly influence the effectiveness of DTN protocols.
- Other solutions: The authors in [8] propose a social mobility model evaluated on two routing protocols. This limited diversity in social mobility models and routing protocols may not accurately reflect the actual complexity of DTN networks. Therefore, simulation results may not realistically reflect the mobility dynamics present in a DTN network and the performance of routing protocols.
- Other solutions: The authors, in [19], present social mobility models to evaluate the performance of DTN protocols. However, this evaluation does not consider the diversity of social mobility models, limiting itself to two social mobility models without taking into account other social mobility models, such as the MRM (Map-Route-Movement) model. The MRM model is very important for simulating mobility in realistic environments, especially urban areas, where mobility is often complex due to population density, variety of routes, variety of vehicles and infrastructure.

9. CONCLUSION

Mobility models are an important factor in evaluating routing-protocols designed for DTN networks. Using inappropriate mobility models for routing-protocols in DTN networks can significantly degrade their performance and applicability in reality. In order to better understand the behaviors of DTN protocols in various social mobility contexts and optimize the use of DTN protocols as well as social mobility models, we have addressed in this article the performance evaluation of the most widely used routing-protocols in DTN networks, Prophet, epidemic, MaxProp and Spray-and-Wait, on the three map-based social mobility models, MRM, SPMBM and MRM. The performance evaluation was carried out using the O-N-E simulator taking into account four performance metrics, Average latency, Delivery rate, Average hop count and Overhead ratio. The simulation results obtained according to the density of nodes show that social mobility models have a significant effect on both the performance of DTN routing-protocols and the routing process in DTN networks. Indeed, the performance of the protocols can vary considerably from one map-based social mobility model to another. This effect can be interpreted by the mobility model adopted by mobile nodes and the specific characteristics of each routing protocol in DTN networks. Generally, DTN routing-protocols demonstrate excellent performance in the context of the SPMBM social mobility model, and average performance in the context of the MBM model, but they demonstrate mediocre performance in the context of the MRM model. Additionally, Spray-

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and-Wait and Maxprop routing-protocols are more effective in realistic environments that include buildings, roads, and social attraction zones. However, other DTN protocols, such as Epidemic and Prophet, demonstrate lower efficiency.

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