

# Impact of Mobility on Mobility Assisted Information Diffusion (MAID) Protocols

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**Abstract**—In this study, we define a class of protocols that utilize mobility for information diffusion in wireless networks, that we call MAID. Such protocols can be used for resource discovery, routing or node location, and hold great promise for future wireless networks. MAID uses encounter history information to create time (or age) gradients towards the target.

We develop analytical models to analyze MAID's performance during the warm-up and the steady state phases. We further conduct extensive simulations to evaluate our models and further understand the effect of mobility on MAID. We provide the first study on sensitivity of this class of protocols to a rich set of mobility models (Manhattan, Group, Random Walk and Random Waypoint models). We find that MAID is sensitive to the mobility pattern. However, to our surprise, MAID's performance after warm-up is insensitive to velocity. Our analysis identifies the characteristics of the *age gradient tree* as the key factor to explain this interplay between mobility and the performance of MAID protocols.

## I. INTRODUCTION

Mobility is a major factor impacting the performance of wireless ad hoc networks (MANETs). While mobility poses several challenges by frequently changing the network connectivity and topology, it also provides opportunities that can, and in fact should, be utilized to enhance the performance of MANET protocols. Recently, the general concept of mobility utilization has been explored in [9] [6] [7] [12] [13] by exploiting the inherent user mobility to facilitate packet delivery. Others, explicitly use the node encounter history to locate (and establish routes to) other nodes [5] [8]. In all these protocols, the mobility assists in diffusing information (whether encounter history or packets) throughout the network. In this paper, we define an abstraction for the above class of protocols that we refer to as the Mobility Assisted Information Diffusion (MAID) protocols.

The MAID protocols provide mobility-assisted mechanisms and building blocks for various essential services in mobile networks, such as efficient resource discovery, routing and node location, among others. One instantiation of MAID uses node encounter history and age to create time gradients within the network. By following the time (or age) gradient, a mobile user can efficiently establish routes to, or locate, other users. The age gradients are created according to the node encounter patterns, which in turn depend on the node mobility patterns. Therefore, to develop deep understanding of the performance of such protocols in various environments, it is necessary to analyze the effect of (and interaction between) a rich set of mobility patterns and the MAID protocol mechanisms. We present the first such study in this paper.

Several proactive and reactive routing protocols have been proposed for routing in MANETs over the past decade (e.g., DSR, AODV, DSDV, TORA, etc.). Recent studies (e.g., [2], [4]) analyze effects of mobility on such protocols. However, MAID protocols are fundamentally different from the conventional, proactive and reactive, routing protocols in several ways: (1) Whereas conventional protocols establish a path and forward the packets in the spatial domain, MAID establishes and forwards the information via time gradients (that are built using mobility). (2) Conventional routing protocols include route discovery and maintenance phases, while MAID includes encounter history caching and anchor search/forwarding phases. Through our study, we shall show that the effect of mobility on MAID protocols is radically different from its effect on conventional MANET routing protocols.

In this paper, we aim to (1) develop a deep insight into the protocol mechanisms for the mobility-assisted encounter based protocols and (2) gain a better understanding of the interaction between the MAID protocols and the mobility patterns. Particularly, we are interested in answering the following specific questions:

- 1) How does mobility impact the MAID mechanisms, including caching, diffusion and node search/location?
- 2) How does the performance of the MAID protocols vary with different mobility patterns and velocity? and Why?

We use both theoretical analysis and extensive simulations to answer these questions. First, we develop an analytical model for the evolution of the encounter cache throughout the network during the warm-up phase. We present a closed form solution to the expected number of encounters with time and the expected warm-up time. Second, we develop an analytical model for the search and location metrics (including path length and cost) and obtain a recursive formula as a solution. We use our results to provide initial insight into the general operation and performance of the MAID mechanisms. The analytical solutions we provide are not specific to a particular mobility model.

We then conduct extensive simulations using a rich set of mobility models, including Manhattan model, Group mobility, Random walk and Random waypoint mobility models. Through simulations, we find that MAID takes a fraction of the warm-up time to reach a steady state during which its performance stabilizes over time. We also find that the warm-up behavior is highly sensitive to both the mobility model

and node velocity. However, to our surprise, the steady state behavior is only affected by the different mobility patterns but is insensitive to the node velocity.

To explain why such result is observed, we introduce the *age gradient tree (AGT)* and study its characteristics. Such tree represents the distribution of the mobility-diffused information throughout the network. We identify a key characteristic related with the AGT called the *temporal-spatio correlation* that refers to the property of having 'fresher' encounter ages closer to the destination. Through simulation, we observe that temporal-spatio correlation exists in all the mobility models we studied. We use such observation to explain the insensitivity of MAID to velocity for the various mobility models. Our analysis, findings and insights pave the road for further research in the area of mobility-assisted protocol design. The contributions of this study include:

- 1) We define a general class of encounter-based mobility-assisted protocols (MAID), and identify two main phases of its operation: the transitional (warm-up) and the steady-state phases.
- 2) We develop novel analytical models to capture performance of MAID in those two phases and validate our models through extensive simulations, over a rich set of mobility models.
- 3) We provide the first sensitivity study for the MAID protocols and conclude that the steady state behavior of MAID is insensitive to velocity, but sensitive to the mobility pattern.
- 4) We introduce a new metric – age gradient tree – as key part of our analysis to explain the interaction between mobility and MAID. We capture the temporal-spatio correlation to reason about the steady state behavior and its insensitivity to velocity.

The outline of the paper is given as follows. we first discuss the previous studies on related topics in Section II. In Section III, we present the general form of MAID protocol and its mechanism. To fully understand the MAID protocol behavior, we develop and present two set of analytical models in Section IV and Section V. After introducing the mobility models and simulation settings in Section VI, we present the simulation results and validate our models in Section VII. We then discuss the interaction between mobility, age gradient tree and MAID protocol performance in Section VIII. Finally, we conclude the paper and lay out our research plan in Section IX.

## II. RELATED WORK

Mobility is observed as one of the key factors impacting the routing protocol performance in MANET. Much of the previous research was based on the evaluation of routing protocols like DSR, AODV and DSDV by using Random Waypoint model. Ref. [4] concluded that reactive protocols such as DSR and AODV outperformed proactive ones such as DSDV at high mobility rates. Realizing that Random Waypoint model may be too simple to capture the rich characteristics of realistic mobility scenarios, Ref. [10] conducted a scenario-based performance analysis, and Ref. [2] used an even richer

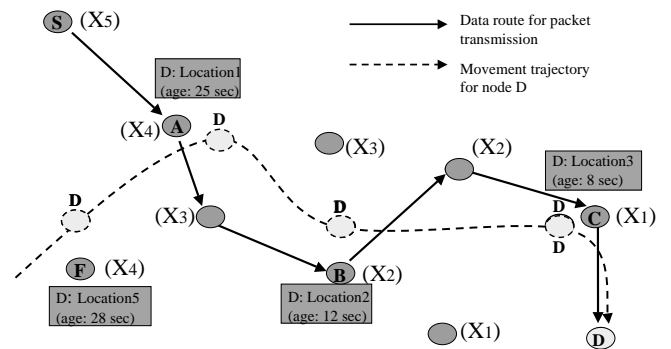


Fig. 1. The Example of MAID Protocol Operation. In this example, to better illustrate how MAID protocol works, we assume that all the other node except node D are stationary. Here, the  $(X_n)$  symbol indicates the hop length of this node to destination, in terms of SPT distance. For example, via SPT tree, node C is 1-hop from destination D, and node B is 2-hops from destination.

set of mobility models to evaluate these MANET routing protocols. Both papers further validated the previous finding that mobility does significantly affect the performance of MANET routing protocols. In this paper, however, we do not plan to study the conventional ones (i.e., based on spatial information). Rather, we attempt to analyze another new class of routing protocols which solely rely on last encounter information between nodes (i.e., temporal information).

Mobility is only used as the evaluation factor in the above studies. Ref. [9] showed that node mobility can be utilized to dramatically improve network capacity. It was the first work to point out that mobility can be a positive factor. A large number of works were then proposed to overcome network partition or facilitate packet delivery by utilizing node mobility, such as Infostation [7], DataMule [12], SWIM [13], DTN [6], Message Ferry [15]. Beside them, EASE [8] and FRESH [5] fall into a new category of discovery protocols explicitly use last encounter information. The intuition behind such schemes is that node encounter history generally provides a rough yet useful estimation about the current network topology. Thus, with the node encounter information, when a query packet travels towards destination, it is able to successively refine the estimation of the destination's location. EASE is a geographic location discovery scheme that solely relies on information about node encounter history (both the time and location of node encounters). The analytical and simulation results indicated that efficient location lookups can be made based solely on encounter history, in Random Waypoint and Random Walk models [8]. Even if the geographic location of node encounters is unknown, the last encounter still could be used to improve protocol performance (i.e., significantly reduce the search overhead), as shown in FRESH [5].

Different with these two studies, in this paper, the MAID protocol is proposed as a general form of the encounter-based MANET routing protocol. Our study mainly focuses on examining the complicated interaction between various mobility patterns and mobility-assisted MAID protocol. To do so, (1) beside the Random Walk and Random Waypoint models in [8] [5], we use an even richer set of mobility

models for protocol evaluation, and (2) the analytical models we developed are not only restricted to specific Random Walk model (as shown in [8]), but also are appropriate for various mobility models. Also, (3) our analytical models enable the analysis of the complicated relationships between mobility, age gradient tree and MAID protocol performance (in terms of warm-up time, expected path length and expected search cost), rather than only focused on the asymptotic performance of cost metric in [8].

### III. MOBILITY ASSISTED INFORMATION DIFFUSION(MAID) PROTOCOL

MAID refers to a class of Mobility Assisted Information Diffusion protocols used for resource (or location) discovery or for route search, by explicitly exploiting node encounters. MAID protocol discovers a route to destination over the space domain by gradually approaching the destination over the time domain (i.e., by successively finding the intermediate nodes that have a smaller encounter age with the destination). In other words, different with conventional MANET routing protocols (like DSR and AODV) that purely rely on *spatial information of location* to find the route, the establishment of routes in the MAID protocols is done by the guidance of *temporal information of node encounter*.

The intuition behind this idea is to utilize the so-called *temporal-spatio correlation* that exists in most of realistic mobility patterns. Specifically, we find that the Cartesian distance (spatial information) between two nodes is more or less correlated with the time when they encounter with each other (temporal information). This relationship is called temporal-spatio correlation. As we will elaborate later in Section VIII-A, we find that temporal-spatio correlation exists in all the mobility models we study in this paper.

#### A. Mechanisms of MAID Protocol

The node encounter history is the key component facilitating the route establishment in the MAID protocol. Thus, the mechanisms of MAID protocols are centered on how to record and utilize the node encounter history. Thus, the operations of MAID protocol consist of two mechanisms, encounter caching mechanism and route searching mechanism.

**Encounter caching mechanism** is in charge of recording the encounters between nodes. As two mobile nodes move within the transmission radius range, both nodes record the time of encounter and the ID of the other node into their node encounter table. If the nodes know their location, this data could also be recorded. If this is the first encounter for the two nodes, a new entry is created at the encounter table of each node. Otherwise, the entries for the other nodes are updated with the newest information. Initially, each node only caches the nodes within its direct neighborhood. We call this phase of protocol operation as *cold-cache phase*. Later, along with the time, each node is able to encounter more nodes. After the node has encountered a large portion of the other nodes, it is able to develop a richer and more accurate view of the whole network topology. At this phase, we claim that MAID

protocols operate at the *warm-cache phase*. Clearly, sufficient encounter events (and, hence the time) are needed to populate (warm up) the encounter tables, so that MAID protocol can gradually change from the 'cold-cache' phase to the 'warm-cache' phase. Thus, we call this time of cache state transition as the *warm-up time*.

**Route Searching Phase** takes the responsibility of finding the routes, based on the cached node encounter history. Each node is able to utilize node encounter history to discover the destination node, by iteratively finding a series of intermediate nodes which had encountered the destination with the decreasing encounter age<sup>1</sup> for the given destination. First, the source aims to find any intermediate node that encountered the destination more recently than the source node itself in its neighborhood. Then, the intermediate node searches for the next intermediate node that encountered the destination even more recently. This way, the search procedure is repeated until it finally reaches at the destination. The nodes which have encountered with the destination before are called *anchor nodes* (or *anchors*). In each search step, an anchor with a larger encounter age is called *upstream anchor* and an anchor with a smaller encounter age is called *downstream anchor*. The search is conducted according to the search method, in a manner similar to the expanding ring search<sup>2</sup>.

As illustrated in Fig.1, the source node  $S$  utilizes the MAID protocol to discover the destination node  $D$ . Node  $S$  first searches in its neighborhood and discovers node  $A$  (that encountered node  $D$  25 sec ago) as its downstream anchor, and node  $A$  then finds node  $B$  (that encountered node  $D$  12 sec ago). Node  $B$ , in turn, finds node  $C$  (that encountered node  $D$  8 sec ago) as the next anchor. Finally, node  $C$  directly locates node  $D$  in its neighborhood.

#### B. Discussion on Design Choices of MAID protocols

The mechanism presented above is general description of MAID-type protocols. The MAID protocols could have other variants, in terms of detailed mechanisms. For example, (1) the cached encounter information not only includes the time of encounter and the ID of the other node, but also may include the location information and other encounter history information (such as frequency of encounter); (2) the search method could be fixed-incremental expanding ring search (e.g., 1,2,3,4..., until  $D$  hops. Here,  $D$  is the network diameter), or exponentially-incremental expanding ring search (e.g., 1,2,4,8..., until  $D$  hops); (3) the search strategy could be either greedy (encounter age of downstream anchor must be less than the encounter age of upstream anchor) or the binary (encounter age of downstream anchor must be less than half of the encounter age of upstream anchor).

<sup>1</sup>Encounter age ( $AGE$ ) is the difference of the current time and the node encounter time, and it indicates the 'freshness' of node encounters.

<sup>2</sup>The upstream anchor first aims to find the potential candidate for the downstream anchor in its direct (1-hop) neighborhood. If such a candidate could not be located, the upstream anchor would keep increasing its search radius and conducting the search again, until a satisfactory candidate of downstream anchor could be discovered.

This way, MAID protocol can be parameterized. We have analyzed several instantiations of MAID protocol. Due to space limitation, we will present result for only one of these studies, however, the conclusions and methodologies presented in this paper also apply to the other studies (refer to Ref. [1] for details)<sup>3</sup>, such as EASE [8] and FRESH [5]. In this paper, the design choices of studied MAID protocol are as follow: Only the time of encounter is recorded; the fixed-incremental expanding ring search; and the greedy search strategy.

### C. Age Gradient Tree for MAID Protocol

As discussed in Section III-A, in the MAID protocol, each upstream anchor is responsible for discovering its downstream anchor. This way, source node eventually finds the destination via a series of concatenated links, with each link pointing from an upstream anchor with larger encounter age to a downstream anchor with smaller encounter age. This set of concatenated links forms an *age gradient path* from the source to the destination, and the encounter ages of the anchors along the age gradient path strictly decrease. For a given destination, the collection of age gradient paths from various source forms an *Age Gradient Tree (AGT)* rooted at this destination. Clearly, the data packets in MAID protocol are sent to destination via the age gradient tree<sup>4</sup>.

We believe that age gradient tree plays an important role in determining the protocol performance of MAID protocols under different mobility scenarios. As will be shown later, we develop analytical model to illustrate how the size of the age gradient tree (i.e., expected number of encountered nodes) is affected by mobility during the cold-cache phase in Section IV. Then, in Section V, we develop analytical models to study how the characteristics of the age gradient tree affect the MAID protocol behaviors when it reaches the warm-cache phase. Furthermore, based on the analysis in Section VIII, we validate our conjecture that age gradient tree is the key to explain MAID protocol performance under various mobility scenarios.

## IV. ANALYTICAL MODEL FOR NODE ENCOUNTERS AND WARM-UP TIME

In this section and Section V, we aim to develop a set of analytical models to analyze the impact of mobility on the protocol mechanisms of MAID protocol, in order to answer the question raised in Section I.

Once MAID protocol starts the operations, for each node, its age gradient tree keeps expanding, when it encounters with more other nodes. In this way, the MAID protocol smoothly transits from cold-cache phase to warm-cache phase. We believe that the *number of encountered nodes*  $E_i(t)$  (i.e., the number of nodes that node  $i$  has encountered before time  $t$ ) is an important indicator to capture the cache warm-up

<sup>3</sup>Please note, for lack of space, we are not able to present all the derivation procedure of analytical models, the figures and tables, the conclusion and observations. Please refer to our technical report [1].

<sup>4</sup>In contrast, in the conventional routing protocols, the packets are sent to destination via the Shortest Path Tree (SPT). In general, the Age Gradient Tree is different from the Shortest Path Tree.

process of MAID protocol. To obtain a deeper understanding, we are particularly interested in developing analytical model to identify the relationship between the number of node encounter and its various impacting factors, including time, node velocity, radius range and mobility patterns. Therefore, we are able to clarify the potential impact of various system parameters on the system warm-up process.

### A. Terminology

Before we develop the simple analytical model, we first define the terms used in our analysis as follows.

- 1)  $N$ : The number of mobile nodes in the network.
- 2)  $A$ : The width of the square-shape network field.
- 3)  $t$ : The time elapsed since the system starts,  $0 \leq t \leq T$ , where  $T$  is the overall system operational time.
- 4)  $R$ : The radius range of each wireless node.
- 5)  $v$ : The average node velocity of mobile nodes.
- 6)  $E_i(t)$ : The expected number of encountered nodes for node  $i$  at time  $t$ , i.e., number of created (not updated) encounter table entries.
- 7)  $\rho$ : The average node density in the simulation field.
- 8)  $p_i(t)$ : The probability for node  $i$  that a node encountered at time  $t$  is really a node that node  $i$  never encountered in the history.

Note that if the mobile nodes are uniformly distributed over the simulation field, then, the node density is  $\rho = \frac{N}{A^2}$ . In general, this is not valid for various mobility models and node distributions. Hence, in general, we assume that the node density is  $\rho = \delta \frac{N}{A^2}$ , where  $\delta$  is the constant compensation factor for the non-uniformly(restricted) fashion of node distribution under different mobility models. Different mobility models have different  $\delta$  values.

Also, for random mobility model, for node  $i$ , the probability of encountering a new node (not encountered before) is  $p_i(t) = \frac{N - E_i(t)}{N}$ . But, in general, to consider all the mobility models, we assume that the probability of being the freshly encountered node is  $p_i(t) = \kappa \frac{N - E_i(t)}{N}$ , where  $\kappa$  is the constant compensation factor for the non-uniform node encounter probability distribution, under different mobility models. Different mobility patterns have different  $\kappa$  values.

Next, we develop an analytical model for the expected number of encountered nodes under various mobility scenarios.

### B. Expected Number of Encountered Nodes

First, let us examine the number of nodes that node  $i$  encountered during the time slot  $\Delta t$  (after time  $t$ ), i.e.,  $E_i(\Delta t|t)$ . During that time slot, the node  $i$  will travel in the distance  $v\Delta t$ , and the area covered by the wireless transmitter of node  $i$  is  $v\Delta t \times 2R = 2Rv\Delta t$ . Because the node density in the field is  $\rho$ , the number of nodes that node  $i$  encountered during time slot  $\Delta t$  is  $2Rv\Delta t \times \rho$ . Within these encountered nodes, some are the nodes that node  $i$  has never encountered in the past, and others are the nodes that node  $i$  has encountered before. Thus, the number of 'freshly' encountered nodes for node  $i$

during time slot  $\Delta t$  (after time  $t$ ) is

$$E_i(\Delta t|t) = v\Delta t \times 2R \times \rho \times p_i(t) \quad (1)$$

$$= \delta\kappa(2vR\Delta t) \frac{N}{A^2} \frac{N - E_i(t)}{N} \quad (2)$$

Clearly, the number of encountered nodes at time  $t + \Delta t$  is the sum of the number of encountered node at time  $t$  and the number of 'freshly' encountered nodes in the time slot  $\Delta t$ . Hence,

$$\begin{aligned} E_i(t + \Delta t) &= E_i(t) + E_i(\Delta t|t) \quad (3) \\ &= (1 - \delta\kappa \frac{2vR}{A^2} \Delta t) E_i(t) + \delta\kappa \frac{2vRN}{A^2} \Delta t \end{aligned}$$

Let  $\alpha = \frac{2vR}{A^2}$ ,  $\beta = \frac{2vRN}{A^2}$  and  $\lambda = \delta\kappa$ . Then, by using the above equation, we have

$$\frac{E_i(t + \Delta t) - E_i(t)}{\Delta t} = \frac{dE_i(t)}{dt} = -\lambda\alpha E_i(t) + \lambda\beta \quad (4)$$

Eqn.4 is a standard differential equation about the unknown function  $E_i(t)$ . Its general solution is given by

$$E_i(t) = \frac{\beta}{\alpha} + ce^{-\lambda\alpha t} = N + ce^{-\lambda\frac{2vR}{A^2}t} \quad (5)$$

where  $c$  is a constant factor to be determined.

When  $t = 0$ , the nodes are static, and the encountered nodes are those within the radius range. Thus, the initial(boundary) condition is  $E_i(0) = \lambda\pi N (\frac{R}{A})^2$ . Therefore, the constant factor  $c = (\lambda\pi(\frac{R}{A})^2 - 1)N$ , and **the number of encountered nodes over time** is (refer to Ref. [1] for details)

$$E_i(t) = N + N(\lambda\pi(\frac{R}{A})^2 - 1)e^{-\lambda\frac{2vR}{A^2}t} \quad (6)$$

The number of encountered nodes is an exponentially incremental function of simulation time  $t$ . At the moment  $t = 0$ , the average number of encountered nodes for each node is  $E_i(t = 0) = \lambda\pi N (\frac{R}{A})^2$ . This is exactly the expected number of nodes within radius range. Then the number of encountered nodes increases with time. When the simulation time is long enough (i.e., approaches to infinity), the expected number of encountered node is  $E_i(t \rightarrow \infty) = N$ . At that time, it is more likely that any specific node has already encountered all the others. Note that when  $E(t)$  is large enough (i.e., larger than a big portion of overall node number), the characteristics of age gradient tree (i.e., the entries in the encounter table) become relatively steady. The protocol then reaches a steady state, we shall elaborate more on this in Section VII.

This analytical model shown in Eqn.6 establishes the relationship between the number of encountered nodes  $E_i(t)$  and various parameters including velocity  $v$ , radius range  $R$  and  $\lambda$  value (Here, we believe that different mobility patterns have different  $\lambda$  values). Thus, we are able to gain a deep insight into how the operation of MAID protocol smoothly transits from cold-cache phase to warm-cache phase, under various system parameter settings.

### C. System Warm-up Time

From Eqn.6, we are able to estimate the system warm-up time based on the system parameters. In line with the observation that the operation of MAID protocols changes from cold-cache phase to warm-cache phase after a node in average has encountered with a portion of other nodes, we define the *warm-up time*  $t_{warmup}$  as the time when the node encounter ratio exceeds a portion (i.e.,  $\gamma$ ) of all the other nodes in average<sup>5</sup>. Hence, we have the inequality

$$\frac{E_i(t_{warmup})}{N} = 1 + (\lambda\pi(\frac{R}{A})^2 - 1)e^{-\lambda\frac{2vR}{A^2}t_{warmup}} \geq \gamma \quad (7)$$

By solving this inequality, we get **the warm-up time** as

$$t_{warmup} \geq \frac{\ln(\frac{1-\gamma}{(1-\lambda\pi(\frac{R}{A})^2)})}{-\lambda\frac{2vR}{A^2}} \quad (8)$$

From Eqn.8, we can see that the warm-up time is a function of the node velocity  $v$ , radius range  $R$ , width of network field  $A$ , and constant compensation factor  $\lambda$  which is unique for each mobility model.

## V. ANALYTICAL MODELS FOR EXPECTED PATH LENGTH AND EXPECTED SEARCH COST

After the warm-up time, the nodes have cached enough encounter information such that the properties of encounter table are stabilized. We are particularly interested in two protocol performance metrics at the warm-cache phase, *expected path length*  $\bar{P}L(x_m)$  and *expected search cost*  $\bar{S}C(x_m)$  of the route generated by MAID protocol (conditional on the given SPT(shortest path tree) distance<sup>6</sup> between source and destination.). Through the derivation, we identify that these two performance metrics are functions of the characteristics of age gradient tree.

### A. Terminology

Before developing the analytical models, we first introduce the terms used in this section.

- 1)  $x_m, x_n$ : The node  $x_m(x_n)$  is the anchor node with  $m$ -hops ( $n$ -hops) SPT distance from the destination. For each search step, the upstream anchor  $x_m$  discovers its downstream anchor  $x_n$  along the age gradient tree ( $\forall n, \forall m, 0 \leq m, n \leq D$ ).
- 2)  $p(x_m, x_n)$ : The probability that upstream anchor  $x_m$  discovers downstream anchor  $x_n$ .
- 3)  $\bar{d}(x_m, x_n)$ : The average distance from upstream anchor  $x_m$  to downstream anchor  $x_n$ , in terms of hop counts.
- 4)  $\bar{c}(x_m, x_n)$ : The average search cost from upstream anchor  $x_m$  to its downstream anchor  $x_n$ , in terms of transmitted packets.
- 5)  $\bar{P}L(x_m)$ : The expected path length from anchor  $x_m$  to the destination via the path computed by the MAID protocol, in terms of hop count.

<sup>5</sup>In our study, we define  $\gamma$  as 30%, as observed through simulations.

<sup>6</sup>The SPT distance between node A and node B, is the number of hops from node A to node B along the Shortest Path Tree rooted at node A

- 6)  $\bar{S}C(x_m)$ : The expected search cost from anchor  $x_m$  to the destination, generated by the MAID protocol, in terms of transmitted packets.
- 7)  $\mu_{n,m}$ : The ratio of the path length for  $x_n$  to the path length for  $x_m$ , in the MAID protocols, where  $n > m$ . In other words,  $\mu_{n,m} = \frac{\bar{P}L(x_n)}{\bar{P}L(x_m)}$ , (where  $n > m$ ).
- 8)  $\nu_{n,m}$ : The ratio of the search cost for  $x_n$  to the search cost for  $x_m$ , in the MAID protocols, where  $n > m$ . In other words,  $\nu_{n,m} = \frac{\bar{S}C(x_n)}{\bar{S}C(x_m)}$ , (where  $n > m$ ).

To give an intuitive insight, we use the example in Fig.1 to illustrate these parameters. For example, node A is one instance of  $x_4$  node because it is 4 hops away from the destination in SPT distance, node B is one instance of  $x_2$  node because it is 2 hops away from the destination. The probability that  $x_4$  node discovers  $x_2$  node as its downstream anchor is  $p(x_4, x_2)$ . The average distance between  $x_2$  and  $x_4$  is defined as  $\bar{d}(x_4, x_2)$  (in the specific case shown in Fig.1,  $d(x_4, x_2) = 2$ ). The average search cost from  $x_2$  to  $x_4$  is defined as  $\bar{c}(x_4, x_2)$  (in the specific case shown in Fig.1,  $c(x_4, x_2) = 6^7$ ). The average path length from node  $x_4$  to the destination in MAID protocol is  $\bar{P}L(x_4)$  and the average search cost from node  $x_4$  to the destination in MAID protocol is  $\bar{S}C(x_4)$ .

The parameters  $p(x_m, x_n)$ ,  $\bar{d}(x_m, x_n)$  and  $\bar{c}(x_m, x_n)$  are the characteristics of the age gradient tree representing the probability, the expected distance and the expected cost from the upstream anchor to the downstream anchor, respectively. Next, we develop a set of analytical models so that the MAID protocol performance could be related with the characteristics of age gradient tree.

### B. Expected Path Length

In the MAID protocol, each upstream anchor  $x_m$  is in charge of searching its downstream anchor  $x_n$  along the age gradient tree. The average distance from the upstream anchor  $x_m$  to the downstream anchor  $x_n$  is  $\bar{d}(x_m, x_n)$ . Considering the expected path length for the anchor  $x_n$  is given as  $\bar{P}L(x_n)$ , then, the path length from anchor  $x_m$  to the destination via anchor  $x_n$  is calculated as  $\bar{P}L(x_n) + \bar{d}(x_m, x_n)$ . Also, the probability that upstream anchor  $x_m$  discovers its downstream anchor  $x_n$  is given as  $p(x_m, x_n)$ . Hence,

$$\begin{aligned} \bar{P}L(x_m) &= \sum_{n=1}^D (\bar{d}(x_m, x_n) + \bar{P}L(x_n))p(x_m, x_n) \quad (9) \\ &= \underbrace{\sum_{n=1}^{m-1} (\bar{d}(x_m, x_n) + \bar{P}L(x_n))p(x_m, x_n)}_{(1)} \\ &\quad + \underbrace{(\bar{d}(x_m, x_m) + \bar{P}L(x_m))p(x_m, x_m)}_{(2)} \end{aligned}$$

<sup>7</sup>Note node A has four 1-hop direct neighbors, as shown in Fig.1. During the 1st-time search of expanding ring search(radius=1), node A broadcasts and generates 1 packet; Then, during the 2nd-time search (radius=2), node A and all its direct neighbors broadcast and generates 1 + 4 = 5 packets. At that time, node B is located. Thus, the overall search cost is 6 packets.

$$+ \underbrace{\sum_{n=m+1}^D (\bar{d}(x_m, x_n) + \bar{P}L(x_n))p(x_m, x_n)}_{(3)} \quad (10)$$

where D is network diameter. Here, part(1), part(2) and part(3) corresponds to the cases in which the SPT distance from upstream anchor to the destination ( $m$  hops) is larger than, equal to, or smaller than the SPT distance from the downstream anchor to the destination ( $n$  hops), respectively. The equation could be solved in a recursive manner. For the upstream anchor  $x_m$  with a given hop distance  $m$ , the path length for the downstream anchor  $\bar{P}L(x_n)$  ( $\forall n, n < m$ ) in part(1) is already known. For the case where  $n > m$  (in part (3)), by substituting  $\bar{P}L(x_n) = \mu_{n,m}\bar{P}L(x_m)$ (where  $n > m$ ) into part(3) of Eqn.10 and then simplifying Eqn.10 (refer to Ref. [1] for details), we get the expected path length for anchor  $x_m$  along the path obtained by MAID protocol as

$$\bar{P}L(x_m) = \frac{\sum_{n=1}^D \bar{d}(x_m, x_n)p(x_m, x_n) + \sum_{n=1}^{m-1} \bar{P}L(x_n)p(x_m, x_n)}{1 - p(x_m, x_m) - \sum_{n=m+1}^D \mu_{n,m}p(x_m, x_n)} \quad (11)$$

### C. Expected Search Cost

The search cost is also an important performance metric to evaluate the MAID protocol, reflecting the initial effort to search the path. Using the same technology for developing the analytical model for expected path length, we get

$$\begin{aligned} \bar{S}C(x_m) &= \sum_{n=1}^D (\bar{c}(x_m, x_n) + \bar{S}C(x_n))p(x_m, x_n) \quad (12) \\ &= \underbrace{\sum_{n=1}^{m-1} (\bar{c}(x_m, x_n) + \bar{S}C(x_n))p(x_m, x_n)}_{(1)} \\ &\quad + \underbrace{(\bar{c}(x_m, x_m) + \bar{S}C(x_m))p(x_m, x_m)}_{(2)} \\ &\quad + \underbrace{\sum_{n=m+1}^D (\bar{c}(x_m, x_n) + \bar{S}C(x_n))p(x_m, x_n)}_{(3)} \quad (13) \end{aligned}$$

where part(1), part(2) and part(3) corresponds to the cases in which the SPT distance from upstream anchor to the destination ( $m$  hops) is larger than, equal to, or smaller than the SPT distance from the downstream anchor to the destination ( $n$  hops), respectively. By substituting  $\bar{S}C(x_n) = \nu_{n,m}\bar{S}C(x_m)$ (where  $n > m$ ) into part(3) of Eqn.13 and then simplifying Eqn.13 (refer to Ref. [1] for details), we get the expected search cost for anchor  $x_m$  to find the destination in MAID protocol as

$$\bar{S}C(x_m) = \frac{\sum_{n=1}^D \bar{c}(x_m, x_n)p(x_m, x_n) + \sum_{n=1}^{m-1} \bar{S}C(x_n)p(x_m, x_n)}{1 - p(x_m, x_m) - \sum_{n=m+1}^D \nu_{n,m}p(x_m, x_n)} \quad (14)$$

#### D. Estimations of Parameter $\mu_{n,m}$ , $\nu_{n,m}$ and Discussion

In this section, we present the approximated estimations for the parameters  $\mu_{n,m}$  in Eqn.11 and  $\nu_{n,m}$  in Eqn.14. Through our theoretical derivations (refer to Ref. [1] for detailed discussion), we find that the path length of MAID paths is linearly correlated with its SPT path length. Hence, the parameter  $\mu_{n,m}$  is

$$\mu_{n,m} = \frac{\bar{P}L(x_n^{MAID})}{\bar{P}L(x_m^{MAID})} \approx \frac{n}{m} \quad (15)$$

Also, we find that search cost of MAID path is polynomially correlated with its SPT path length. To be in details, the parameter  $\nu_{n,m}$  is also a function of their SPT distances (please refer to Appendix of Ref. [1] for the detailed derivation), as

$$\nu_{n,m} = \frac{\bar{S}C(x_n^{MAID})}{\bar{S}C(x_m^{MAID})} \approx \frac{2n^3 - 3n^2 + n}{2m^3 - 3m^2 + m} \quad (16)$$

We validate both Eqn.15 and Eqn.16 by taking the measurement of the path length ratio  $\mu_{n,m}$  and search cost ratio  $\nu_{n,m}$  (where  $n > m$ ) in the MAID protocol, through simulations. The results indicate that, in most cases, Eqn.15 and Eqn.16 are reasonable approximations of real scenarios<sup>8</sup>.

After replacing the  $\mu_{n,m}$  factor and  $\nu_{n,m}$  factor by Eqn.15 and Eqn.16, we get the analytical models for **the expected path length and the expected search cost** in the MAID protocol as

$$\bar{P}L(x_m) = \frac{\sum_{n=1}^D \bar{d}(x_m, x_n) p(x_m, x_n) + \sum_{n=1}^{m-1} \bar{P}L(x_n) p(x_m, x_n)}{1 - p(x_m, x_m) - \sum_{n=m+1}^D \frac{n}{m} p(x_m, x_n)} \quad (17)$$

$$\bar{S}C(x_m) = \frac{\sum_{n=1}^D \bar{c}(x_m, x_n) p(x_m, x_n) + \sum_{n=1}^{m-1} \bar{S}C(x_n) p(x_m, x_n)}{1 - p(x_m, x_m) - \sum_{n=m+1}^D \frac{2n^3 - 3n^2 + n}{2m^3 - 3m^2 + m} p(x_m, x_n)} \quad (18)$$

As shown in Eqn.17, for a given  $m$  value, the expected path length  $\bar{P}L(x_m)$  is a function of the characteristics of age gradient tree ( $\bar{d}(x_m, x_n)$ ,  $p(x_m, x_n)$ ) and the expected path length of the paths whose SPT distance smaller than  $m$  hops

<sup>8</sup>We acknowledge that the both equations (Eqn.15 and Eqn.16) are only the approximations of the realistic scenarios. However, the accuracy of the analytical models (Eqn.11 and Eqn.14) will not be significantly affected. This is because, intuitively, we know that it is a rare case that an upstream anchor will search a downstream anchor whose SPT distance to destination is even much larger than its own SPT distance to the destination. Through the simulation, we observe that  $p(x_m, x_n)$  is a very small value if  $m \leq n \leq m + \varepsilon$ , and  $p(x_m, x_n) = 0$  if  $n \geq m + \varepsilon$  (in most mobility scenarios,  $\varepsilon \leq 2$ ). At the same time, the value  $p(x_m, x_n)$  (where  $n < m$ ) seems to be a very large value compare to the value  $p(x_m, x_n)$  if  $n > m$ . That is to say, even the approximation of  $\mu_{n,m}$  and  $\nu_{n,m}$  is not exactly accurate, the small values of  $p(x_m, x_n)$  ( $n > m$ ) enables the item  $\sum_{n=m+1}^D \mu_{n,m} p(x_m, x_n)$  (in Eqn.11) and  $\sum_{n=m+1}^D \nu_{n,m} p(x_m, x_n)$  (in Eqn.14) to be very small values. Thus, the accuracy of the estimation based on Eqn.17 and Eqn.18 will not be affected significantly by these approximations made in Eqn.15 and Eqn.16. We further validate our argument through extensive simulations

( $\bar{P}L(x_n)$ , where  $1 \leq n < m$ ). Similarly, as shown in Eqn.18, for a given value  $m$  value, the expected search cost is also a function of the characteristics of age gradient tree ( $\bar{c}(x_m, x_n)$ ,  $p(x_m, x_n)$ ) and the expected search cost of the paths whose SPT distance smaller than  $m$  hops ( $\bar{S}C(x_n)$ , where  $1 \leq n < m$ ).

Here, both expected path length  $\bar{P}L(x_m)$  and expected search cost  $\bar{S}C(x_m)$  are dependent on their counterparts  $\bar{P}L(x_n)$  and  $\bar{S}C(x_n)$  for the paths with smaller SPT hop lengths ( $n < m$ ). Therefore, both Eqn.17 and Eqn.18 should be solved in a recursive fashion, from smallest  $m$  value ( $m = 1$ ) to the largest  $m$  value ( $m = D$ ). Intuitively, the initial conditions for recursive-format Eqn.17 and Eqn.18 are  $\bar{P}L(x_1) = 1$  and  $\bar{S}C(x_1) = 1$ . Starting from these initial conditions, we are able to estimate the expected path length  $\bar{P}L(x_m)$  and expected search cost  $\bar{S}C(x_m)$  based on these two analytical models, if the characteristics of age gradient tree ( $\bar{d}(x_m, x_n)$ ,  $\bar{c}(x_m, x_n)$ ) and  $p(x_m, x_n)$  are given. As shown in the Section VII, we validate both analytical models via the simulations.

The characteristics of age gradient tree  $p(x_m, x_n)$ ,  $\bar{d}(x_m, x_n)$  and  $\bar{c}(x_m, x_n)$  are directly measured from the simulation. In our study, we realize that the characteristics of age gradient tree are the dominant factors that affect the MAID protocols performance under different mobility scenarios. At the same time, as will be seen in Section VIII-B, we also find that the characteristics of age gradient tree indirectly reflect the effect of mobility patterns and node velocity on node connectivity graph. Thus, we believe that characteristics of age gradient tree is the key bridge to explain the relationship between mobility and MAID protocol performance. We will discuss this in details in Section VIII-C.

## VI. SIMULATION SETTING

Before we evaluate the MAID protocol, we first discuss the mobility models used in our study and the simulation parameter settings in this section.

### A. Mobility Models

In order to thoroughly examine the performance of MAID protocol, we evaluate and analyze the MAID protocols over a rich set of mobility models, including Random Waypoint(RWP), Random Walk(RWK), Reference Point Group Mobility(RPGM) and Manhattan mobility(MH) model. This set of mobility models is carefully chosen so that each of them exhibits the different mobility characteristics. We describe these mobility models as follows:

(1) **Random Waypoint(RWP) model:** In RWP model, each mobile node randomly selects one location in simulation field as its destination and moves towards it with a randomly chosen speed. Upon reaching the destination, the node stops for a certain time period, after which, it moves towards another randomly chosen destination with a random speed. In RWP model, the node velocity is independent of other nodes. However, for a given node, the current node velocity depends on its previous one. Hence, RWP exhibits a strong degree of temporal correlation and weak degree of spatial correlation.

(2) **Random Walk (RWK) model:** In RWK model, the nodes change their speed and direction at each time interval. For every new interval  $t$ , each node randomly chooses its new direction  $\theta(t)$  and the new speed  $V(t)$ . Both RWK and RWP model exhibit strong randomness, while RWK model exhibits a weak degree of temporal correlation.

(3) **Reference Point Group Mobility (RPGM) model:** RPGM model is used to model group mobility. Here, each group has a group leader and a number of group members. The group leader determines the motion behavior for the whole group, while each group member chooses a velocity by randomly deviating from its group leader. The node movement in RPGM model is correlated with its groupmates. Thus, the RPGM model is expected to show a strong degree of spatial correlation between the different nodes.

(4) **Manhattan Mobility (MH) model:** MH model emulates the node movement on streets. Manhattan grid maps of horizontal and vertical streets are used to restrict the node movement. On each street, the mobile nodes move along the lanes of both directions. At each intersection, the mobile nodes choose their directions with certain probability. The speed of mobile node is also randomly chosen. Unlike RWP model, the mobile nodes only travel on the pathways in the map.

As discussed above, these models represent a rich set of mobility characteristics varying from weak to strong degrees of temporal correlation, spatial correlation and geographic restriction. We believe that this rich set of mobility models cover the mobility design space with different mobility characteristics, providing a solid basis to evaluate and analyze the MAID protocols.

### B. Simulation Setting

To evaluate MAID protocol over various mobility models, we carry out the simulation in the customized event-driven simulator developed by the authors. The mobility traces are obtained through the IMPORTANT mobility scenario generator [2]. This scenario generator produces the different mobility patterns following RWP, RWK, RPGM and MH models according to the format required by *ns-2*. In all these patterns, 400 mobile nodes move in an area of 3000m by 3000m for a period of 4000 seconds. The value for the radius range is set as the default value(250m). For RPGM, 80 groups (with five nodes for each group) are moving independent of each other and in an overlapping fashion. To tackle the well-known speed decay problem [14], we set the minimum speed as 3m/s for all the mobility patterns. The maximum speed is set to 5, 10, 20, 30, 40 and 50m/s to generate different movement patterns for the same mobility model.

The data traffic pattern consists of 100 pairs of CBR data traffic. For each pair, both source and destination are uniformly chosen from all the nodes. The data rate used is 4 packet/second. To eliminate effects caused by the randomness of the traffic pattern, we used different random seeds to generate five different traffic patterns for each mobility scenario.

Beside the metrics mentioned in Section IV and Section V, we are also particularly interested in examining two perfor-

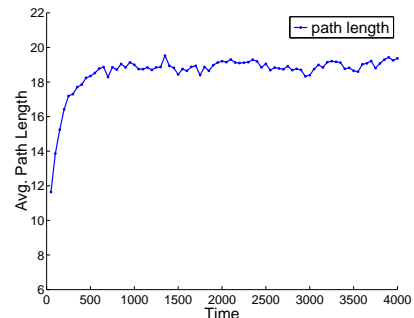


Fig. 2. The Average Path Length of MAID Protocol vs. Time (RWK model,  $V=5\text{m/s}$ )

mance metrics, *overall average path length*  $\bar{P}L$  and *overall average search cost*  $\bar{S}C$ <sup>9</sup>, across various mobility models.  $\bar{P}L$ (or,  $\bar{S}C$ ) is the path length of route (or, the number of search packets) generated by the MAID route, averaged over all the source-destination pairs. With these two performance metrics, together with other metrics mentioned in Section IV and Section V, we are able to quantitatively evaluate and compare the MAID protocol under different scenarios in the next section.

## VII. SIMULATION RESULTS

Extensive simulations were conducted to answer the question *How MAID protocol is affected by the underlying mobility scenarios?*, in Section VII-A and Section VII-B, respectively. Beside that, in Section VII-C and Section VII-D, we also aim to measure the protocol performance and validate the proposed analytical models. The matching between analytical results and simulation results is satisfactory. This indicates that our analytical models provide a good approximation to estimate the MAID protocol performance, based on the measurement of the age gradient tree.

### A. Transitional Behavior and Steady Behavior

We record the values of  $\bar{P}L$  and  $\bar{S}C$  at each time instance. Interestingly, we found that the MAID protocol performance cannot be stabilized at the initial phase of simulation. For example, in RWK model,  $\bar{P}L$  constantly keeps increasing (as shown in Fig.2) and  $\bar{S}C$  keeps decreasing (as shown in Fig.3) as the time elapses. Both of them become relatively stable after some time (around 545 seconds) and reach a steady state. Thus, **the operation of the MAID protocol can be divided into two states: initial transitional state and follow-up steady state**. Such a phenomenon is not unique to RWK model, we also observe the similar phenomenon for RWP, RPGM and MH models at different node velocities during the simulations (refer to Ref. [1] for details).

This phenomenon is caused by the different caching phases of the MAID protocol. At the cold-cache phase, MAID protocol mostly relies on the flooding mechanism to search the

<sup>9</sup>Note that  $\bar{P}L$  is not  $\bar{P}L(x_m)$  and  $\bar{S}C$  is not  $\bar{S}C(x_m)$ . In fact,  $\bar{P}L$  (or,  $\bar{S}C$ ) is the weighted summation of  $\bar{P}L(x_m)$  (or,  $\bar{S}C(x_m)$ ). That is,  $\bar{P}L = \sum_{n=1}^D (p_n \bar{P}L(x_n))$ . And also,  $\bar{S}C = \sum_{n=1}^D (p_n \bar{S}C(x_n))$ . Here,  $p_n$  is the probability that the SPT distance of source-destination pair is  $n$  hops.

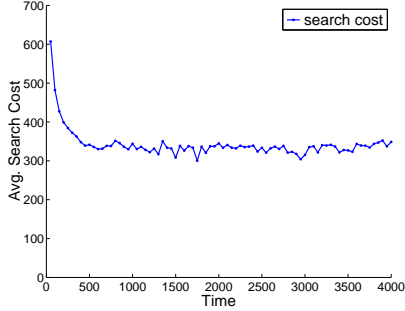


Fig. 3. The Average Search Cost of MAID Protocol vs. Time (RWK model,  $V=5\text{m/s}$ )

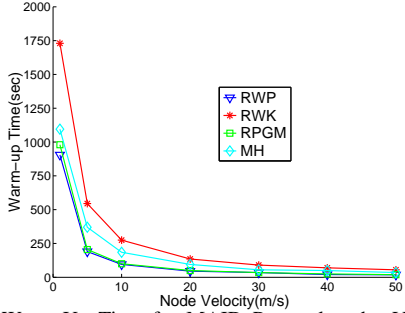


Fig. 4. The Warm Up Time for MAID Protocol under Various Mobility Models

route, since it is difficult to find the intermediate ‘anchor’ with appropriate cache. Thus, the path obtained is optimal (i.e., closer to the SPT path) at the expense of large search costs. However, once the cache reaches the warm-cache phase, the MAID protocol could utilize several intermediate ‘anchors’ to find the destination. Hence, the path becomes less optimal but the search cost is significantly reduced.

### B. Transitional Behavior and Steady Behavior vs. Mobility

In this section, we plan to investigate the impact of mobility on MAID protocol performance, at both transitional state and steady state. Specifically, we examine the warm-up time  $t_{warmup}$  (transitional-state behavior) as well as overall average path length  $PL$  and overall average search cost  $SC$  (steady-state behavior), across the different mobility scenarios.

As shown in Fig.4, we observe that, to ensure the enough node encounters and stabilize the protocol performance, the MAID protocol needs the different warm-up time for different mobility models and different node velocities. For the same node velocity, different mobility models need different warm-up time. For the same mobility model, in general, the higher node velocity setting requires the lower warm-up time.

We also examine the MAID protocol performance at steady state across various mobility scenarios, as shown in Fig.5 and Fig.6. For the same node velocity, both  $PL$  and  $SC$  are different for different mobility models. However, at the same time, for the same mobility model, both of them rarely vary with the different node velocity settings.

Intuitively, the MAID protocol is supposed to be highly sensitive to the underlying node mobility process. However, out of our expectation, we find out that **the MAID protocol performance at transitional state is sensitive to both mobil-**

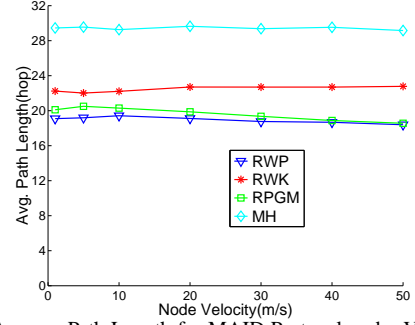


Fig. 5. The Average Path Length for MAID Protocol under Various Mobility Models

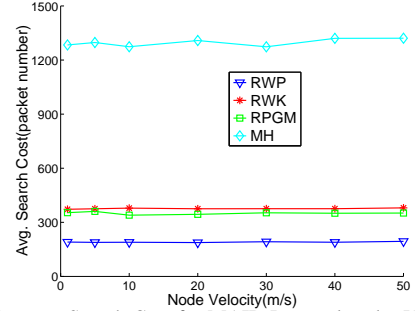


Fig. 6. The Average Search Cost for MAID Protocol under Various Mobility Models

**ity model and node velocity setting, while its steady state behavior is only sensitive to underlying mobility model but robust to node velocity.** With the deeper analysis presented in Section VIII, we attempt to explain these unexpected observations.

### C. Expected Number of Encountered Nodes (Transitional Behavior)

In this section, we analyze how the expected number of encountered nodes  $E_i(t)$  increases with time, under various mobility scenarios. This metric helps us to capture the transitional behavior of the MAID protocol.

We observe that the expected number of encountered nodes is a monotonically increasing function of time under all the mobility patterns. For a given node velocity, the curves are different under different mobility patterns, as shown in Fig.7. Among them, the curve for RWK model is the lowest, the RWP and RPGM model are the highest ones, while the MH model lies in between. We also examine the effect of node velocity on the expected number of encountered nodes. As shown in Fig.8, in RWP model, we observe that the expected number of encountered nodes increases faster when the node velocity becomes larger. Similar results are also observed for RWK, RPGM and MH models (refer to Ref. [1] for details). The extensive simulations further strengthen our observation made in Section VII-B: *the MAID protocol performance at transitional state is sensitive to both the mobility model and the node velocity setting.*

We also attempt to validate the analytical model shown in Eqn.6. Thus, we applied the curving fitting scheme [11] to compare the experiment results collected from simulations and the analytical results based on Eqn.6. we compare the error

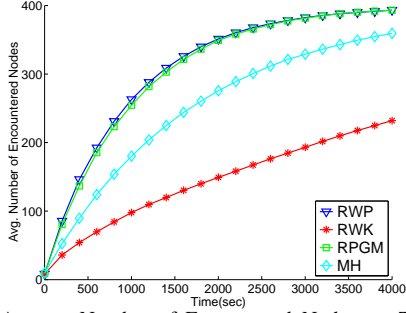


Fig. 7. The Average Number of Encountered Nodes vs. Time for all the Mobility Models ( $v=10\text{m/s}$ )

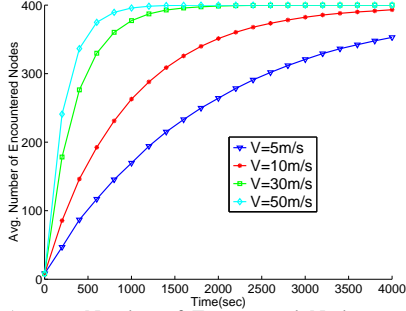


Fig. 8. The Average Number of Encountered Nodes vs. Time for RWP Model

margin ratio between the simulation results and the best-fit curve obtained from the analytical model. We find that the error margin ratio appears to be very small ( $\leq 2\%$  in most cases), across all the mobility models. This fact indicates that our analytical model shown in Eqn.6 is good model to approximate the transitional behavior of the MAID protocol.

Via the maximum likelihood test [11], we also estimate the  $\lambda$  values in Eqn.6. We observe that the  $\lambda$  parameter is different for various mobility patterns, while it is nearly same for the different node velocities under the same mobility pattern. This observation is consistent with our initial conjecture made in Section IV. The average  $\lambda$  parameter for RWP, RWK, RPGM and MH models are 1.92325, 0.71454, 1.8324 and 0.94365, respectively (refer to Ref. [1] for details).

#### D. Expected Path Length and Expected Search Cost (Steady Behavior)

After analyzing the transitional behavior of the MAID protocol in Section VII-C, we examine the detailed steady behavior of the MAID protocol in this section. Specifically, we look at both expected path length  $\bar{P}L(x_n)$  and expected search cost  $\bar{S}C(x_n)$  for the route with given SPT distance ( $n$  hops). Fig.9 and Fig.10 illustrate  $\bar{P}L(x_n)$  and  $\bar{S}C(x_n)$ , under various mobility models at a given node velocity. The x-axis in both figures is the SPT hop distance between a source and a destination, and the y-axis is the expected path length  $\bar{P}L(x_n)$  or expected search cost  $\bar{S}C(x_n)$  for the path with the given SPT distance, respectively.

As shown in Fig.9,  $\bar{P}L(x_n)$  increases with the SPT hop distance  $n$  for all the mobility patterns. For a given SPT hop distance, the path length for the MH model is the highest and the RWK model has the lowest value, while the values

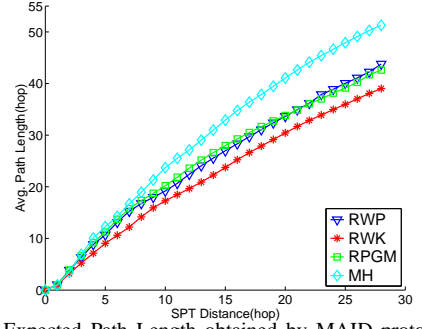


Fig. 9. The Expected Path Length obtained by MAID protocol for all the Mobility Models ( $v=10\text{m/s}$ )

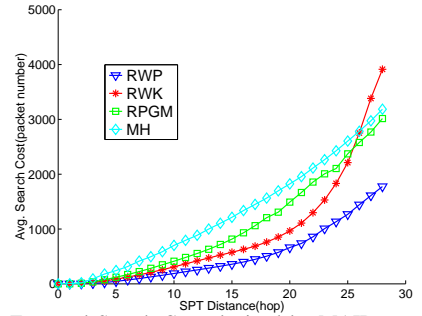
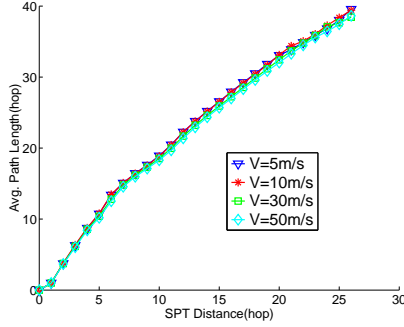


Fig. 10. The Expected Search Cost obtained by MAID protocol for all the Mobility Models ( $v=10\text{m/s}$ )

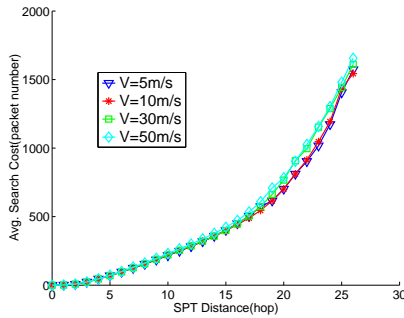
for RWP and RPGM models are nearly same and lie in the between. As shown in Fig.10,  $\bar{S}C(x_n)$  increases with the SPT hop distance  $n$  for all the mobility patterns. For a given SPT hop distance, the RWP model generates the lowest overhead, and the other three mobility models are crossing over each other. When the hop distance  $n$  is small, the MH model incurs the larger search cost than the RWK and RPGM model.

We also examine the effect of node velocity on the steady behavior of MAID protocol for a given mobility model. We observed that the steady behavior of the MAID protocol is insensitive to the node velocity for a given mobility pattern. Both  $\bar{P}L(x_n)$  and  $\bar{S}C(x_n)$  for RWP model are illustrated in the Fig.11. Obviously, the different node velocity settings barely have an effect on the steady behavior of the MAID protocol, in terms of either the trend of the curve or the detailed values. Similar results are also observed for RWK, RPGM and MH models (refer to Ref. [1] for details). These observations again validate our previous observation: *the MAID protocol at steady state is robust to different node velocity settings but still sensitive to the mobility patterns.*

Again, we also validate the proposed analytical models shown in Eqn.17 and Eqn.18 via simulations. In these models, both the expected path length  $\bar{P}L(x_n)$  and expected search cost  $\bar{S}C(x_n)$  are the functions of the characteristics of the age gradient tree, including  $p(x_m, x_n)$ ,  $\bar{d}(x_m, x_n)$  and  $\bar{c}(x_m, x_n)$ . We take the measurement of all these characteristics through simulation and then insert them into the Eqn.17 and Eqn.18 to estimate the expected path length  $\bar{P}L(x_n)$  and expected search cost  $\bar{S}C(x_n)$ , under the different mobility scenarios. At the same time, we also directly measure  $\bar{P}L(x_n)$  and  $\bar{S}C(x_n)$  from the simulation.



(a) The Expected Path Length



(b) The Expected Search Cost

Fig. 11. The Steady-State Protocol Performance under RWP Model, for Different Node Velocities.

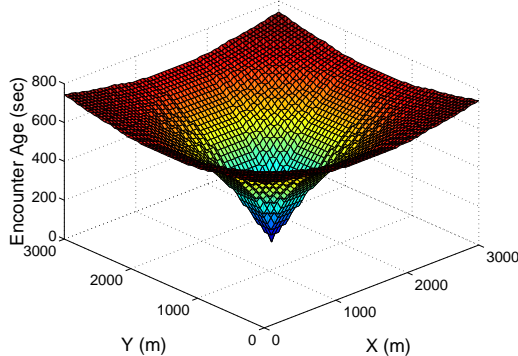


Fig. 12. The Temporal-Spatio Correlation for the RWK model ( $V=30\text{m/s}$ ), Measured from Simulation.

Then, we compute the error margin ratio between the calculated result and the measured result [11]. Through the study, we find the error margin ratio for the expected path length is 5% – 10% and the error margin ratio for the expected search cost is around 6% – 17% in most mobility scenarios. The acceptable error margin ratios show that the analytical result still matches with the simulation result in most cases, indicating that the proposed analytical models (Eqn.17 and Eqn.18) are good approximations to study the steady behavior of MAID protocol (refer to Ref. [1] for details).

### VIII. THE LOGICAL RELATIONSHIP BETWEEN MOBILITY, AGE GRADIENT TREE AND MAID PROTOCOL PERFORMANCE

In this section, we attempt to answer questions *Why MAID protocol is(or, is not) affected by the underlying mobility*

*scenarios?* asked in Section I and explain the observations made in Section VII, by putting all the components together. Thus, we are able to establish a clear logical relationship among the mobility, the temporal-spatio correlation, the age gradient tree and the MAID protocol performance.

#### A. Temporal-Spatio Correlation and Age Gradient Tree

Intuitively, the temporal-spatio correlation exists for most mobility scenarios, including all the mobility models discussed in this paper. Nodes tend to be far away from each other if they encountered a long time ago, and vice versa. Thus, we are able to roughly estimate the distance between nodes, based on their last encounter time. However, note that the relationship between spatial distance and encounter age is not a deterministic one, since the node mobility has some degree of irregularity. Also, different mobility models exhibit different types of temporal-spatio correlation.

To vividly illustrate the temporal-spatio correlation, we examine the 3-D *age gradient field*. For a specific destination, the age gradient field is formed if each node on the 2-D space is associated with its encounter age for the destination, which represent the ‘potential’ (similar to the meaning of ‘potential’ in physics). Thus, in the 3-D graph, the x- and y-axis represents the x- and y-position of a node, and z-axis indicates its encounter age with the destination. As shown in Fig.12, the age gradient field for the RWK model is like a funnel (whose sink is the destination), indicating the spatial distance between a node and destination is somehow correlated with their encounter age. Similarly, the temporal-spatio correlation is also clearly observed for RWP, RPGM and MH models (refer to Ref. [1] for details).

The age gradient field implicitly designates the route between any mobile node to the given destination, by following its trajectory towards the sink on the funnel surface. At each search step, the upstream anchor node finds the nearest downstream anchor node with smaller encounter age (i.e., the node with lower ‘potential’ in the age gradient field) on the funnel surface. Because of the inherent temporal-spatio correlation, the packets gradually moves from upstream anchor towards downstream anchor and finally reaches the destination. Hence, we believe that **the temporal-spatio correlation is the key reason enabling the mobility-assisted encounter-based MAID protocol.**

In the normal operation of the MAID protocol, the temporal-spatio correlation is not directly used. Instead, the 3-D temporal-spatio correlation is projected onto the 2-D space. Correspondingly, the set of implicit designated routes on the funnel surface are also projected onto the 2-D space, forming an age gradient tree (this is exactly the age gradient discussed in Section III-C). Therefore, the age gradient tree is an abstracted form of the temporal-spatio correlation. In our study, we mainly focus on investigating the characteristics of age gradient tree under various mobility scenarios and understanding their impact on the MAID protocol performance.

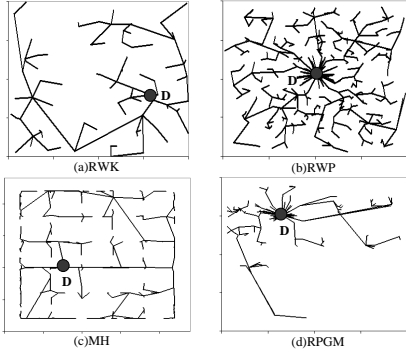


Fig. 13. The Age Gradient Tree (AGT) for RWP, RWK, MH and RPGM models ( $v=20\text{m/s}$ ,  $t=400\text{sec}$ ). Here, D is the destination (also, the root of AGT).

### B. The Impact of Mobility on Age Gradient Tree

For a given destination, its age gradient tree evolves over time, as its size increases. Hence, the shape and the characteristics of the age gradient tree also keep changing over time, until the node has already encountered with a certain portion of other nodes. After reaching the warm-cache phase, both the shape and the characteristics of age gradient tree will not change drastically. During the warm-up process, both **mobility model and node velocity seem to play a major role in determining how fast the size of the age gradient tree grows.**

At steady state, we are interested in examining how the shape and the characteristics of age gradient tree behave under different mobility patterns and different velocities. First, we discuss the case of different mobility models with same node velocity. Intuitively, different mobility patterns create different encounter patterns and hence the different temporal-spatio correlations. As shown in Fig.13, the shape of age gradient tree for RWK, RWP, RPGM and MH mobility models are visually different (and so are their characteristics). For example, in the MH model, the age gradient tree consists of age gradients on the horizontal and vertical lines because nodes are restricted to the Manhattan map (as shown in Fig.13(c)).

Next, we examine the case of same mobility model with different velocity settings. Here, interestingly, we observe that the shapes and characteristics of age gradient tree for the same mobility model are similar under the different node velocity settings. With the different node velocity settings, the exact encounter age between nodes may differ and the height of 3-D temporal-spatio correlation (as shown in Fig.12) may be different. However, its rough shape and the designated routes on the funnel surface (the age gradient from the node with larger encounter age to the node with smaller encounter age) do not change drastically. In other word, once the 3-D temporal-spatio correlation is projected to the 2-D field, the information of exact encounter age (z-axis value) becomes useless. Here, only the relative relationship between node encounter ages (i.e., from which anchor to which anchor) does matter. In this way, the node velocity only contributes to ‘scale’ the encounter age but does not affect their relative relationship. Hence, the shapes of age gradient tree under different node

velocity are nearly same for a given mobility model.

In summary, we observe that **the mobility model significantly affects the shape and the characteristics of the age gradient tree, while the node velocity settings may not affect.** It seems that age gradient tree is the key element to explain the interplay between MAID protocol behavior and mobility.

### C. The Relationship between Mobility, Age Gradient Tree and MAID Protocol Performance – Quantitative Approach

In this section, we are interested in analyzing the question *why (or why not) the MAID protocol is sensitive to mobility (at both transitional state and steady state)?*, quantitatively.

For transitional behavior, clearly as shown in Eqn.8, we found that the warmup time  $t_{warmup}$  is the function of both node velocity  $v$  and constant compensation factor  $\lambda$  (which is unique for each mobility model). Thus, different node velocity (different  $v$ ) and different mobility models (different  $\lambda$ ) must have different system warm-up time  $t_{warmup}$ .

For steady behavior, in Section V, we realize that the characteristics of the age gradient tree are the direct factors to determine the MAID protocol performance at the steady state. Also, on the other hand, we believe that the mobility patterns affect the characteristics of the age gradient tree but the node velocity rarely affects them, as shown in Section VIII-B. To validate our conjecture, we take a further step to quantitatively compare the characteristics of age gradient tree at different velocity settings under a given mobility model. First, we take measurement of the value  $p(x_m, x_n)$ ,  $\bar{d}(x_m, x_n)$  and  $\bar{c}(x_m, x_n)$  ( $\forall n, \forall m, 0 \leq n, m \leq D$ ) under different velocity settings, for each mobility model. Then, we calculate the error margin ratio of these three characteristics between different node velocity settings. Through study, we find that, for a given mobility model, the node velocity settings barely impose the impact on the characteristics of the age gradient tree. For example, the error margin ratio for  $p(x_m, x_n)$ ,  $\bar{d}(x_m, x_n)$  and  $\bar{c}(x_m, x_n)$  is less than 5.25%, 4.06% and 8.45% in most cases of all the mobility models (please refer to Appendix of Ref. [1] for detailed comparison results). That is to say, the characteristics of the age gradient tree are nearly same when the node velocity is set to the different values. These quantitative observations are consistent with our intuitive findings in Section VIII-B.

Therefore, we believe that there is a logical relationship between the node mobility, the age gradient tree characteristics and the MAID protocol performance: The age gradient tree exhibits different characteristics under various mobility patterns while these characteristics are nearly same under the different node velocity settings for a given model. Thus, the MAID protocol, which is deterministically impacted by the characteristics of the age gradient tree, behaves differently for various mobility models but it is less sensitive to different node velocities. Therefore, we believe that **the characteristics of age gradient tree are the key bridge linking the mobility**

## effect and the protocol behavior of MAID protocol<sup>10</sup>.

### IX. CONCLUSION & FUTURE WORK

We present Mobility Assisted Information Diffusion(MAID) protocol as a class of routing protocol to establish the route by directly utilizing the last encounter information between mobile nodes. Because the last encounter information is highly dependent on mobility, we call such kind of protocols as mobility-assisted protocol. Thus, in the MAID protocol, mobility factor is not only treated as an evaluation element, but also actively integrated into the protocol design. In this paper, we are very interested in analyzing the potential interaction between the mobility and the MAID protocol.

To achieve this objective, we first develop a set of analytical models to examine the impact of mobility factor on detailed MAID protocol mechanisms, for both warm-up process and steady-state behavior. The results obtained are able to provide initial insight into the general operations of MAID protocol. We then evaluated the MAID protocol over a rich set of mobility models by which we believe that mobility space could be spanned. We found that the transitional behavior of MAID protocol is significantly affected by underlying mobility scenarios, while the steady behavior of MAID protocol is somewhat less sensitive to the node mobility. We believed that the age gradient tree is the key factor to explain these observations. By validating the two set of proposed analytical models we developed in this paper, we confirmed our conjecture that age gradient tree is the key bridge to link node mobility and MAID protocol performance.

In the next step, we plan to continue our research and enhance the MAID protocol mechanism under different scenarios. For example, MAID protocol could be operated under the scenarios of disconnected networks. In such scenarios, the mobile node is able to cache the data packets if the upstream anchor cannot find the downstream anchor. We plan to design such an enhanced MAID protocol. Another research direction is to design a practical protocol whose protocol performance is relatively robust to node mobility, based on the prototype of MAID protocol. The performance of most MANET routing protocols drastically degrades with the increased node velocity. However, through our study, we found that the MAID protocol (based on the age gradient tree) is relatively robust to node velocity under certain conditions. Thus, we are interested in designing another mobility-robustness MANET routing protocol which explicitly utilizes the concept of the age gradient tree.

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<sup>10</sup>The role of age gradient tree in MAID protocol is analogical to that of the time-related connectivity graph characteristics (such as Link Duration and Path Duration) in the SPT-based MANET routing protocols [3]. We believe that, because of the different protocol mechanisms, it is necessary to examine the different connectivity graph properties which are directly relevant to the protocol mechanism.