Make Multi-hop Broadcast in VANET Fast by Selecting a Better Route for Source Vehicle

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***Abstract*—Vehicular Ad-Hoc Network (VANET) connects a vehicle to nearby vehicles and infrastructures through wireless networks. Over the last decades, various VANET unicast, multicast, and broadcast protocols have been proposed and studied extensively. In this paper, we dive into the study of VANET multi-hop broadcast from a new angle: How should the source vehicle select its route so that its message can be delivered to all vehicles (in a selected area) fastest? We will call this problem *RAB (Route-Assisted Broadcasting)*. The use of "route selection" as a strategy to minimize broadcast latency has never been explored to the best of our knowledge.**

This study deepens our understanding of the intricate interplay between a vehicle's mobility and message-passing in VANET. In the past, we usually considered *communication* serves *mobility*, and too much *mobility* hurts *communication* (e.g., high mobility incurs volatile and unstable topology that disrupts communication performance). This study reveals how *mobility* could be used to help *communication*.

Our contributions can be categorized into two main parts: 1) We show that RAB is NP-Hard to solve; 2) We build a highly configurable simulator that explores different routes in canonical mobility models.

***Index Terms*—VANET, multi-hop, broadcast, mobility model, route selection, RAB**

I. Introduction

Vehicular Ad-Hoc Network (VANET) enables vehicle-to-vehicle (V2V) communications and thus allow drivers or self-driving cars to exchange road safety and efficiency information. Broadcast in VANET becomes an vital communication primitive when a vehicle on the road needs to notify all nearby vehicles about a particular message. Latency is one critical performance metric that would affect all the VANET participants. In this paper, we consider the problem of a multi-hop broadcast from a single source to other vehicles in an area using only V2V communication.

We consider only V2V communication because there are certain cases that cellular or infrastructure-assisted communication is not available or too expensive to use (both with respect to monetary cost or network latency cost). For example, when there is a natural disaster like a tsunami, earthquake, or a power outage that disables infrastructures, V2V communication (in particular, our protocols) can be used to spread messages regarding disaster relief, law enforcement, and other emergency information effectively.

This paper focuses on reducing latency of multi-hop broadcast in VANET – How can the source vehicle deliver its message to all other vehicles in an area in the shortest amount of time, with the help of receivers to relay the message? Such a problem has been studied extensively, and we refer readers to comprehensive discussions in two relevant surveys [1], [2]. The new angle in this paper is to fully utilize the mobility of a vehicle to help to shorten message delivery time. We call our problem – *RAB (Route-Assisted Broadcasting)*. In particular, we study the problem of finding an optimal route for the source to move so that all the other vehicles in a fixed area will receive its message fastest.

There are many different versions of the RAB problem. In this work, we focus on the most straightforward formulation, as we want to understand the fundamental properties of RAB: 1) all vehicles stay inside the area (i.e., fixed membership); 2) all other vehicles that received the message will relay it continuously (i.e., gossip model with altruistic nodes); and 3) communication range is fixed and no message is lost. The formal specification of the RAB problem is introduced in Section III. Interesting extensions are presented in Section VII.

Contributions: In this paper, we dive into the study of multi-hop broadcast in VANET from a new angle, namely the RAB problem. We point out the synergy between "mobility" and "communication," which has not been explored in the previous studies. Concretely, we have the following contributions:

- In section IV, we prove that the RAB problem is NP-Hard to solve in general.
- RAB problem seems more tractable in a more practical setting. In particular, we developed a configurable and extensible simulation framework to explore heuristic approaches, which is presented in section V.
- We conduct extensive simulation and present some interesting results in section VI. Our results indicate that those route choices of the source affects the performance significantly in some cases.

II. Related Work

As we mentioned earlier, broadcast or multicast protocols have been popular topics in VANET or MANET (Mobile Ad-Hoc Network). Research topics include, but not limited to, reliability, energy consumption, antenna design, standardized protocols (e.g., DSRC, WiFi), etc. There are both theoretical studies and practical implementations. Please refer to two recent surveys [1], [2] for more details. In this paper, we consider the intricate interplay between mobility and multi-hop broadcast performance. As the first step, we are interested in fundamental understanding; hence, we choose abstract protocols that are easy to implement in practice. Specifically, we consider a discrete-time system using V2V communication where each vehicle adopts a gossip-like protocol – in each time step, vehicles with the message will broadcast to neighboring vehicles, and this is the only way for vehicles to learn the message. Other more advanced protocols are left as interesting future work.

Mobility Models: Since the mobility model is the essential element of the RAB problem, this section is focused on the discussion of relevant mobility models. Mobility models characterize the movement patterns of mobile nodes (e.g., vehicles). Accurate models are essential in studying the effectiveness and the performance of communication protocols. Various mobility models have been proposed (e.g., [3]–[10]), which can be categorized to at least one of the following: stochastic, synthetic, social network-based, and map-based. Synthetic mobility models can be further categorized to models with temporal dependency, with spatial dependency, or with geographical restriction [11]. Here, we only discuss the most relevant ones due to space constraints.

In stochastic models, randomness is embedded in nodes' movement. One of the most widely studied models is the Random Waypoint Mobility Model (RWPMM) [3]. In the original RWPMM, each mobile node randomly selects a velocity and a target to move toward. Upon reaching the target, this mobile node pauses for a certain fixed period and then selects the next velocity and the next target. An extension of RWPMM was studied in [6], in which the "waypoints" have different probabilities of being chosen. The authors also offered an explicit formula to calculate the spatial distribution of mobile nodes in the given region. Another common stochastic mobility model is the Random Direction Mobility Model (RDMM) [4], in which each mobile node randomly selects a direction and a speed to move until it hits a border, and then repeats. Another variation is the Manhattan Grid Mobility Model (MGMM) [5], which is a synthetic mobility model with geographic restriction. In MGMM, at each intersection, a moving mobile node continues the current direction with 50% probability or turn left or right each at 25% probability.

These models have been used to analyze many protocols in VANET or MANET (e.g. [12]–[15]). We have implemented RWPMM, RDMM, and MGMM in our simulator. In Section VII, we discuss how to extend our work to consider more realistic scenarios, by incoporating the notion of "hotspots."

III. System Model and Problem Statement

We formally define our problem below. We first present the models and present our problem formulation.

Vehicle and Movement: In a theoretical setup, we consider the region or a map is specified by a given directed graph. As the first step, we consider a discrete-time setup, where the mobility model dictates the position of each vehicle, who can move from one vertex to one of its outgoing neighbors in one unit of time. In a practical setup, we consider a region $\mathbf{R}$, which could be a 2D plane or 3D torus (i.e., vehicles which move across the left/up broader appears on the right/down, and vice versa). The length and width of $\mathbf{R}$ are both finite, denoted by R_x and R_y, respectively. In both models, we consider static systems, i.e., no vehicle enters or exits the region.

There are $n \in \mathbb{N}^{\geq 2}$ vehicles in the system, and each vehicle can be uniquely identified as $v_1, v_2, \cdots, v_n$. W.l.o.g., vehicle v_1 is the source who has the message initially. Vehicle movement is specified by a given mobility model for each vehicle. The model dictates how each vehicle moves, i.e., speed, direction, pause time, etc. It also specifies the initial position of each vehicle.

Communication and the network: Recall that we model a V2V communication, particularly short-range broadcast. In a graph-based model, the communication range is defined with the scope of a node, whereas in plane- or torus-based models, the communication range is defined using a parameter r. That is, each vehicle is able to transmit and receive messages to every other vehicle if they are on the same vertex or if they are within r unit distance in each case. We assume that the V2V communication is reliable, and occurs in each time step. As mentioned earlier, we consider a simple gossip model. That is, for all the vehicles that already have the messages will relay the message in each time step.

RAB (Route-Assisted Broadcast): Given a region, vehicles, and mobility models for each vehicle, the goal of RAB is to select the route of the source v_1, i.e., the position at each time step, so that all the other vehicles can receive the message in the shortest amount of time. That is, minimize the time between v_1 starts broadcasting to the last vehicle v_k that receives the message.

IV. Hardness of RAB

We will prove that the RAB problem in the theoretical setting is NP-hard by reducing from the well-known Set Cover problem. That is, if we have an efficient algorithm A for the RAB problem, then we have an efficient algorithm for the Set Cover problem by using A as a blackbox.

Theorem 1. *RAB is NP-hard in general.*

Due to space limits, we only present the proof sketch below. Consider an instance I of the NP-complete *Set Cover* problem: Given a set of elements $U = \{1, 2, \ldots, n\}$ and a collection C of m sets whose union equals U, identify k sets from C whose union equals the universe. Our goal is to construct a graph for the region and specific mobility model for each vehicle except for the source such that if there exists an optimal algorithm to find out the route for the source to complete broadcast in the shortest amount of time, then we can use such an algorithm to solve *Set Cover* efficiently.

We construct a *directed* graph $G = (V, E)$ as follows:

- Add a starting node s into V – this is where the initial position of the source.
- For each element $u \in U$, add an "element node" u into V. For a slight abuse of terminology, we will use u to

represent both the element in U and a node in the newly constructed graph G.
- For each set $c \in C$, add a "set node" c into V.
- For each set node c, add (s, c), a directed edge from s to c, and (c, s), a directed edge from c back to s, into E.
- For each pair of set node c and element node u, add (c, u) into E if the element u is in set c of the set cover instance I.
- Add a destination node d into V – this is where the end position of the source.
- Add (s, d) to E.

We need the destination node so that the source has to end somewhere. This simplifies the argument.

Then we have the vehicles and corresponding mobility patterns as follows:

- For each set node c, we will have $|c|$ cars, all of which start at the node c.
- Each vehicle stays at its starting node for $2k$ rounds and move to one of the element node u such that each vehicle from c will move to a different element node at round $2k + 1$. This is possible because there are $|c|$ cars in the system.
- Once the vehicle (except for the source) gets to the element node, it stays there forever.
- There exists a vehicle at d that does not move.

Claim 1. *The set cover instance I is a YES instance of size k if and only if the broadcast can be completed in $2k+1$ rounds (or time steps).*

Proof. If there exist k sets that cover U, then the source vehicle can move to the corresponding set nodes in $2k$ rounds and stops at node d by moving back-and-forth from c's and s. Then in round $2k + 1$, all these informed vehicles will move to element nodes where all vehicles will be at. Thus, any uninformed vehicles will learn the message.

If there does *not* exist a set cover of size k, then under any source route, there will exist an element node u that is *not* covered by any visited cover node. Therefore, the source has to visit u then goes to d next; however, this is not possible, because each element node is a sink. **Q.E.D.**

V. Simulator

Theorem 1 implies that it is computationally infeasible to study the RAB problem in arbitrary graphs. Fortunately, in practice, vehicles often only wander around in a specific area. Moreover, the physical constraints eliminate some edge cases that might be created from arbitrary (theoretical) graphs. We first consider vehicles' movement characterized by canonical mobility models and use simulation to attack RAB. In this work, we present the simulations based on RWPMM, RDMM, and MGMM. For a candidate route, we run the set of parameters (for vehicles' mobility model and the simulation area) under different random seeds. To compare different routes, we run a large number of simulations under the same set of random seeds. We present the parameters, simulation methodology, and our mobility model below. Our code is available at https://github.com/haochenpan/CarsOnTheGrid

A. Initialization

Each simulation run specifies the following parameters. Values we listed in the table below conclude our preliminary results in section VI.

TABLE I: Simulator Configurations

Parameter	Example Values
size of $\mathbf{R}$: R_x, R_y	50 units, 50 units
num. of vehicles: n	25 or 50
broadcast range: r	1 unit
vehicle speed	1 unit per round
mobility models	see table II
source's behavior	see section VI-B

B. Round-based simulation

We first initialize vehicles by assigning them a random seed and a mobility model chose a priori. Then we construct two sets of vehicles, one is $\mathbf{C}$, the set of message carriers (i.e., nodes that have already learned the message), which only contains v_1, the source (or broadcaster), at the beginning. Another is $\mathbf{N}$, which contains all the other vehicles, i.e., message receivers.

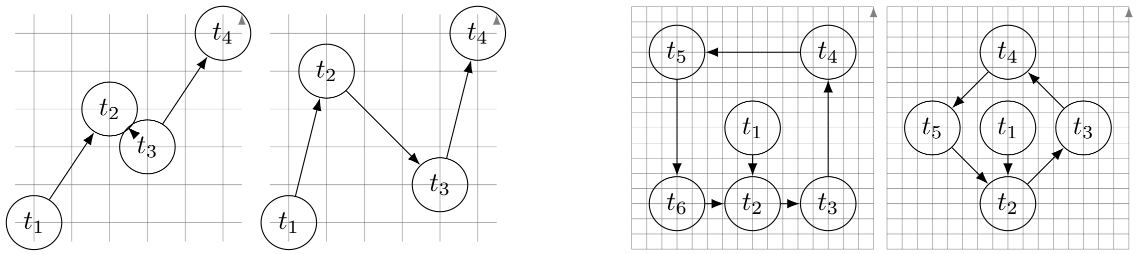
Simulation proceeds in a round-based fashion (namely, discrete-time simulation), vehicles move (first for-loop), and then relay the message if it is a message carrier (second for-loop) at each round. While there are vehicles that have not received the message, each vehicle in $\mathbf{V}$ moves on the simulation area according to the predefined parameter (i.e., the distance it should move) and the mobility model in case of generating a new target to move toward. For each message receiver, if there exists a message-carrier vehicle within the broadcast distance, this vehicle then becomes a message carrier. The simulation terminates when all vehicles receive the message, i.e., all vehicles are in the set $\mathbf{C}$, and we output the number of rounds of the while loop.

VI. Preliminary Results

We present our preliminary results here and identify several interesting observations.

A. Simulation

For a single simulation run, we select one mobility model (e.g., RWPMM-3D) and all vehicles except the initial message carrier (i.e., source) v_1 obey the mobility model. Vehicles other than v_1 are placed uniformly randomly in the simulation area (according to the random seed assigned to each vehicle). To eliminate the cold-start problem, in each simulation run, each non-message carrier vehicle move for 100 rounds according to the selected mobility model. Then, we start executing our simulation by introducing the source vehicle. For each data point, we report the average of 3000 simulations for each configuration, i.e., initializing and broadcasting a message to all vehicles for 3000 trials under the same set of parameters but with different random seeds.



(a) Zigzag23 and Zigzag14

(b) Rectangles

Fig. 1: Routes

B. Routes for Source

We describe routes we choose for the source.

- *Stationary*: the source vehicle stays at the spawn point until the simulation is over, which could be a corner, the center, or the midpoint of a border.
- *Straight-line*: the source vehicle travels along a straight line. If it reaches a border on a 2D map, it goes back on the same route. On a 3D torus, it maintains the direction until the simulation terminates.
- *Zigzag family*: see figure 1a for two members of the Zigzag family: Zigzag23 (t_2's locate at $(5n + 2, 5n + 3)$) on the left and Zigzag14 (t_2's locate at $(5n+1, 5n+4)$) on the right. Like the straight-line routes, the source vehicle has a major moving direction. In every 5x5 grid, a vehicle changes its direction twice; first it goes from t_1 to t_2, then from t_2 to t_3, and finally from t_3 to t_4. It does the same in the next 5x5 grid (see the left-hand side of figure 2a and 2b). This pattern of movement remains until the end of a simulation.

  We also tested routes that are combinations of a zigzag and straight lines: First a zigzag from (0, 0) to (50, 50), then a straight line all the way; or first a straight line from (0, 0) to (50, 50), then a zigzag all the way;
- *Rectangle*: In the left figure of figure 1b, the source vehicle spawns at v_1 $((25, 25))$, and then travels from t_2 to t_6 in a cycle (In the right figure, it travels from t_2 to t_5 in a cycle) and thus its trace is a rectangle. This rectangle could be larger or small, and we tested on one with length (and width) 15 and one with length (and width) 35.

C. Simulation Results

Due to space constraints, we are only able to present results from selected configurations. We summarize some interesting observations below:

1) The map size, shape of the map (2D or 3D), the number of vehicles, and mobility models used greatly affects the broadcast speed.
2) The exponential growth of the number of vehicles that have received the message implies the source vehicle needs to utilize the power of peer vehicles to relay messages.
3) The long tail in the growth graph indicates that there are a few vehicles that receive the message long after most vehicles have received the message.
4) Sometimes zigzag13, zigzag14, a combination of a zigzag with the straight line are better than moving straight ahead in a single run. However, if we consider only the average of a large number of simulation runs, then the benefit is not clear.

Comparing Different Mobility Models: We present our study on five popular mobility models, with the source's moving strategy among one of the three:

- the source vehicle stays at the center $(25, 25)$
- the source vehicle stays at a corner $(0, 0)$
- the source vehicle starts at a corner $(0, 0)$, and moves on the major diagonal

and either with 25 or 50 cars in the simulation area. The average number of rounds needed to complete broadcast in each configuration is presented in the Table II

For RWPMM-2D, RDMM, and MGMM-2D, the source staying at the center would outperform staying at a corner. For RWPMM-3D and MGMM-3D, this does not hold because of the torus feature. Additionally, when there are either 25 or 50 cars, starting at a corner, then moving to the center and continuing to go in this direction is better than staying at the center. This conclusion holds for all mobility models except for RWPMM-2D. The conclusion is that moving is generally better than staying, even better than staying at the center. More importantly, Table II shows that route selection is an effective strategy in most cases. For example, staying at a corner has poor performance in general, more than 50% worse in some cases.

For either 25 or 50 cars under the RWPMM-2D mobility model, the average number of rounds is huge. This result is because the source vehicle stays at (0, 0), and the first broadcast only happens after a few thousands of rounds when a vehicle enters the broadcast region – one forth of a unit circle centered at (0, 0). Therefore, the numbers vary from a few hundred rounds to more than 10 thousands of rounds. A similar trend can be observed in MGMM-2D. In the torus/3D version, this problem is eliminated, because corners and the center are effectively the same.

Route Selection: We tested more routes using RWPMM-3D, a common model used for VANET broadcasting protocol's

TABLE II: Mobility Models Compared

Mobility Model	Stays at the Center		Stays at a Corner		Moves Diagonally	
	25 cars	50 cars	25 cars	50 cars	25 cars	50 cars
RWPMM-2D	234.66	146.69	5601.74	2763.51	261.81	164.67
RWPMM-3D	364.56	218.06	364.36	218.12	349.52	208.99
RDMM	378.61	224.5	547.58	313.19	362.12	220.52
MGMM-2D	596.92	363	859.09	527.16	538.3	339.65
MGMM-3D	482.69	294.73	478.29	295.37	414.61	261.11

TABLE III: RWPMM-3D

The Source's Route	Avg Rounds
Stay at the corner	364.36
Goes straight up	345.74
Goes straight right	348.21
Move diagonally	349.52
Zigzag23	351.77
Zigzag14	352.03

performance. After extensive simulation, we found that there is *no* strategy better than going straight up, or right, or diagonally. Two of our best candidates are Zigzag14 and Zigzag23 (see figure 2a and 2b), which are as good as straight-line strategies and better than staying at the corner (see table III).

VII. Summary and Future Works

In this paper, we study multi-hop broadcast from a new angle – the RAB problem – which investigates how to select the best route for the source to speed up multi-hop broadcasting. We first prove that RAB is NP-hard, and we present an extensible simulator and our preliminary evaluation results. This work can be extended in several ways, which we will discuss next.

RAB Variations: A line of work is to study RAB under constraints or some conditions. For example, in many scenarios, we only require a certain percentage, say 95%, of vehicles to receive the message. Or we can impose an energy consumption threshold, e.g., a relay vehicle can only forward message a certain number of times. One final interesting aspect is to study the optimal number of sources to complete broadcast in a certain number of rounds.

Towards Realistic Mobility Model: PGMM: For advanced and more realistic mobility models, integrating the notion of "hotspots" is useful. There have been two close works on such a study. The definition of hotspots varies in the mobility models literature, e.g., hotspots for hybrid WLAN/Cellular system [7] and shopping mall [8], [9]. These models are not appropriate for VANET. To better connect various mobility models for understanding the RAB problem, we need a new definition of hotspots. In particular, vehicles do *not* necessarily move towards hotspots (e.g., in the shopping mall models [8], [9]), or change their behavior as in the WLAN/Cellular model [7]. Instead, a hotspot is defined as a region that each vehicle would visit more often, i.e., the probability of visiting the region is higher than in other regions. Moreover, we allow the probability to change over time, i.e., our mobility model has a dynamic or time-varying feature.

To better investigate RAB through simulation, we propose the Probability Grid Mobility Model (PGMM). The core of PGMM is the probability grid. A probability grid is a 2D array whose element with index (i, j) represents the probability of point (i, j) on the simulation area been picked as the next target by a vehicle. Therefore, each entry is a real number r between 0 to 1, and the sum of the entire 2D array is 1. To increase the granularity, i.e., allowing picking non-integer targets, one can have a probability grid that has larger length and width. For example, having a 100×100 grid for a 10×10 simulation area allows us to pick (1.1, 0.9) as a target (the associated probability is at index $(11, 9)$).

There are three variations of PGMM: static, dynamic, and local. In the static probability grid mobility model, a single grid is associated with all vehicles, and the probability grid is never changed over the entire period of simulation. The dynamic grid model is still associated with all vehicles, but the probabilities inside the grid may change over time. The local grid model is associated with each vehicle, and thus vehicles have different probabilities in picking a single target (i, j). Note that naturally, for local models, we can have local-static or local-dynamic versions.

Benefits: PGMM offers a unified programming model. Since our simulator supports adding functions and modules, a new mobility model can be implemented to respect PGMM easily. Probability Grid directly reflects the idea of hotspot target, that is, regions that are more likely to be picked. For example, RWPMM has no hotspot (each point has an equal probability of being picked); RDMM creates probability hotspots on borders, and MGMM creates hotspots at integer points. The last two updates when a vehicle reaches a border/crossroad. One important feature is that targets of vehicles are not limited to these hotspots. Compared to [7], [8], PGMM is more realistic, as there is typically no universal hotspots that will attract every mobile node in reality.

PGMM allows vehicles to obey different mobility models. Such abstraction not only simplifies the development of our simulator but also makes it extensible. For example, the broadcaster vehicle can have its mobility models so that its route can be more realistic than a single stream of waypoints. Another example is that a group of vehicles obey different mobility models (city grid vs. high way). Such flexibility and extensible allow us to explore more realistic scenarios.

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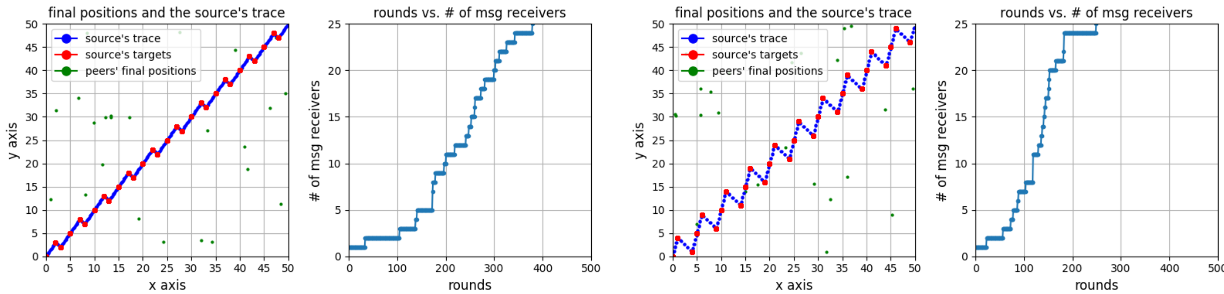

(a) Zigzag23 trace with RWPMM-3D

(b) Zigzag14 trace with RWPMM-3D

Fig. 2: Two example traces and their corresponding rounds vs. $|C|$ statistics

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