On the Effectiveness of Epidemic Broadcast with Directional Transmission in Vehicular Ad-Hoc Networks

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Abstract—**In this paper, we extensively investigate the effectiveness of an epidemic broadcast with directional transmission. In VANETs, realization of broadcast communication from a vehicle to other vehicles solely using a vehicle-to-vehicle communication is desired. In our previous work, we have proposed *DSCF (Directional Store-Carry-Forward)*, which is an epidemic broadcast with directional transmission. DSCF is a simple epidemic broadcast but it intentionally performs directional transmission for alleviating the broadcast storm problem. In this paper, we extensively investigate the effectiveness of DSCF on a two-dimensional road model in terms of *reachability, dissemination speed, uniformity, and efficiency*. The performance of DSCF is thoroughly compared with that of P-BCAST (Push-based BroadCAST), which is one of the simplest epidemic broadcasts with omnidirectional transmission. In theory, P-BCAST achieves the optimal reachability, dissemination speed, and uniformity while compromising the worst efficiency. Our findings include that DSCF can achieve satisfactory reachability and dissemination speed comparable to those of P-BCAST with significantly better efficiency, which implies favorable characteristics of directional transmission for epidemic broadcasts in VANETs.**

Keywords-**ITS (Intelligent Transport Systems); VANET (Vehicular Ad-hoc Network); DTN (Delay Tolerant Network); epidemic broadcast; directional transmission; DSCF (Directional Store-Carry-Forward)**

I. INTRODUCTION

Recently, various kinds of research on DTNs have been actively performed for realizing diverse types of applications toward ubiquitous society [1]. One of the promising application areas of DTNs is VANET (Vehicular Ad-hoc NETwork). In VANETs, a vehicle may or may not find other vehicles within its communication range because of vehicles' mobility, which results in frequently intermittent vehicle-to-vehicle communication. Because of such an unstable communication environment, it is indispensable to adopt a DTN-aware communication mechanism in VANETs.

In VANETs, for instance, broadcast communication from a vehicle to other vehicles solely using a vehicle-to-vehicle communication is required [2, 3]. If road traffic information (e.g., traffic congestion, traffic regulation, and road condition) and/or local area information (e.g., information on parking lots and gas stations) can be delivered to vehicles in a timely fashion, drivers' convenience and safety are well improved. A vehicle-to-vehicle communication is available without infrastructures, such as base stations and relay stations. Thus, delivery of road traffic information and local area information might be realized at a very low cost.

In [4], we have proposed *DSCF (Directional Store-Carry-Forward)*, which is an epidemic broadcast with directional transmission. DSCF is a simple epidemic broadcast but it intentionally performs directional transmission. With directional transmission, DSCF alleviates the well-known problem called *broadcast storm problem* [5]. The effectiveness of DSCF on a one-dimensional road model has been analyzed in [4]. Also, preliminary performance evaluation of DSCF has been performed in [6]. Moreover, in [7], we have discussed the requirements on broadcast communication, and have investigated performance evaluation of directional communication though simulation experiment. However, the effectiveness and essential property of DSCF not fully clarified.

In this paper, we extensively investigate the effectiveness of DSCF in terms of *reachability, dissemination speed, uniformity, and efficiency* based on discussion in [7]. The performance of DSCF is thoroughly compared with that of P-BCAST (Push-based BroadCAST) [8], which is one of the simplest epidemic broadcasts with omnidirectional transmission. P-BCAST transmits messages whenever a vehicle finds other vehicles within its communication range, hoping that the message will

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eventually be delivered to all other vehicles. Although there have been several epidemic broadcast mechanisms with omnidirectional transmission in the literature (see [8-10] and references therein), we use P-BCAST as a baseline because of its simplicity. In theory, P-BCAST achieves the optimal reachability, dissemination speed, and uniformity while compromising the worst efficiency. Through extensive simulations, we investigate the impact of directional transmission on epidemic broadcasts in VANETs. Also, we mathematically analyze DSCF to understand the essential property of epidemic broadcasts with directional transmission.

The rest of the paper is organized as follows. Section II summarizes related research activities on epidemic broadcasts with either omnidirectional or directional transmission in VANETs. Section III presents the overview of DSCF, followed by explanation on its operation algorithm. Section IV performs extensive simulations for investigating the effectiveness of DSCF on the two-dimensional road model. In Section V, we mathematically analyze DSCF. Finally, Section VI concludes this paper and discusses future work.

II. Related Work

A number of epidemic broadcasts (i.e., opportunistic flooding-based communication mechanisms) in DTNs have been proposed [8-10]. In epidemic broadcasts, messages are propagated among nodes as like a spread of diseases. Namely, when a node with a message (i.e., infected node) contacts other nodes without a message (i.e., susceptible nodes), the infected node sends a copy of the message to those susceptible nodes.

In epidemic broadcasts, one of the challenges is to prevent the *broadcast storm problem* by controlling and/or suppressing redundant transmissions of duplicate messages. If an epidemic broadcast is used in a network with high node density, a node frequently contacts with other nodes. Hence, the epidemic broadcast generally results in excessive overhead [5].

In the literature, several techniques for reducing the amount of redundant transmissions of duplicate messages in epidemic broadcasts have been proposed [11-15]. In [11, 12], adaptive controls of the message transmission rate have been proposed. In [13], history-based mechanisms of transmission control have also been proposed. In [14, 15], suppression mechanisms of excessive rebroadcast packets in broadcast communication have been proposed.

On the other hand, usage of directional transmission has been actively studied in conventional (i.e., non-epidemic) broadcast communication for MANETs (Mobile Ad-hoc NETworks) [16-18]. In [16-18], the effectiveness of directional transmission for conventional broadcast communication has been extensively investigated. Those studies clearly suggest that directional transmission is promising for reducing the amount of message duplicates. It is naturally expected that such directional transmission should also be beneficial to epidemic broadcasts in VANETs because of its potential for alleviating the broadcast storm problem. To the best of our knowledge, however, the effectiveness of directional transmission for epidemic broadcast in VANETs has not been fully investigated although there exist several simulation studies on one-dimensional road models [4].

III. DSCF (Directional Store-Carry-Forward)

DSCF enables broadcast communication from a vehicle to other vehicles solely using a vehicle-to-vehicle communication [4]. Every vehicle has two communication ranges, where a vehicle can detect existence of and communicate to other vehicles. The shapes of both communication ranges are semicircle with radius R_D. When a vehicle receives a message, the vehicle can determine the communication range where the message is received. With these communication ranges, DSCF performs broadcast communication.

DSCF employs a store-carry-and-forward data delivery for broadcast communication. When a vehicle holding messages finds other vehicles within its communication range, the vehicle transmits the message to those vehicles. Otherwise, the vehicle conveys the message until it encounters other vehicles. Hence, DSCF can continue broadcast communication against intermittent vehicle-to-vehicle communication because of its store-carry-and-forward data delivery.

To alleviate the broadcast storm problem [5], DSCF performs directed message delivery using directional transmission. Every vehicle receives a message only from one direction and transmits the message to the opposite direction. A message received via a communication range is relayed to other vehicles via the other communication range.

Figure 1 illustrates an example of the directional transmission in DSCF. In this figure, vehicle $C2$ receives the message from vehicle $C1$ in a communication range, and transmits the message to vehicle $C3$ in the opposite communication range.

Figure 2 illustrates an example of the store-carry-and-forward in DSCF. In this figure, we only draw commu-

First, vehicle $C1$ transmits a message to vehicle $C2$. Then, vehicle $C2$ conveys the message until vehicle $C2$ finds vehicle $C3$ in the communication range of its sending direction. When vehicle $C2$ finds vehicle $C3$ in the communication range of its sending direction, vehicle $C2$ transmits the message to vehicle $C3$. Vehicle $C3$ then relays the message to all adjacent vehicles $C4$, $C5$ and $C6$.

IV. Simulation

A. Experiment Setup

In this paper, we extensively investigate the effectiveness of DSCF on the two-dimensional road model in terms of *reachability, dissemination speed, uniformity,*

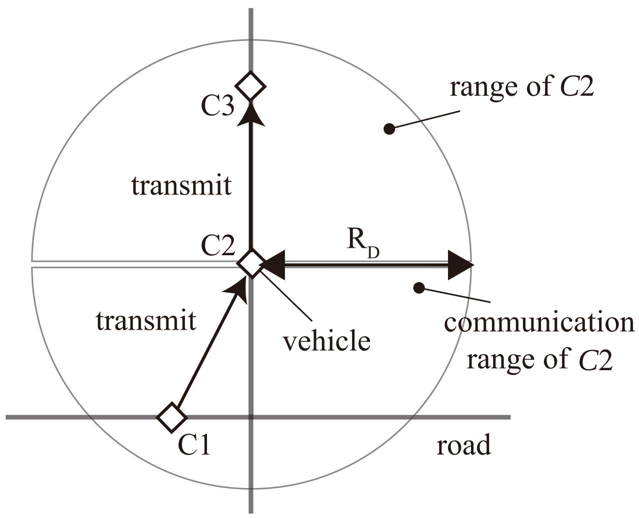

Fig. 1: To alleviate the broadcast storm problem, DSCF performs directional transmission. In this figure, an example of directional transmission in DSCF is illustrated.

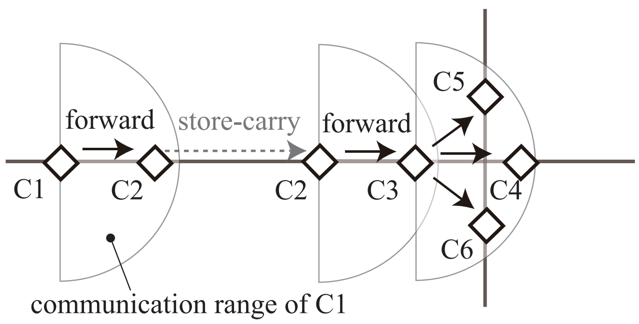

Fig. 2: An example of the store-carry-and-forward in DSCF; In this figure, a message is to be propagated from left to right by performing the store-carry-and-forward of vehicle C1 through C6.

and efficiency. The performance of DSCF is thoroughly compared with that of P-BCAST [8], which is one of the simplest epidemic broadcasts with omnidirectional transmission. P-BCAST transmits messages whenever a vehicle finds other vehicles within its communication range, hoping that the message will eventually be delivered to all other vehicles.

Although there have been a large number of epidemic broadcast mechanisms with omnidirectional transmission in the literature (see [8-10] and references therein), we use P-BCAST as a baseline because of its simplicity. In theory, P-BCAST achieves the optimal reachability, dissemination speed, and uniformity while achieving the worst efficiency. The main difference between DSCF and P-BCAST is the number of transmissions per vehicle. DSCF is a single-transmission epidemic broadcast while P-BCAST is an infinite-transmission one. Thus, the long-term behaviors of DSCF and P-BCAST are quite different; i.e., broadcast communication with DSCF terminates once the message is delivered to other vehicles, but broadcast communication with P-BCAST infinitely continues. We are therefore only interested in comparing the short-term behaviors of DSCF and P-BCAST.

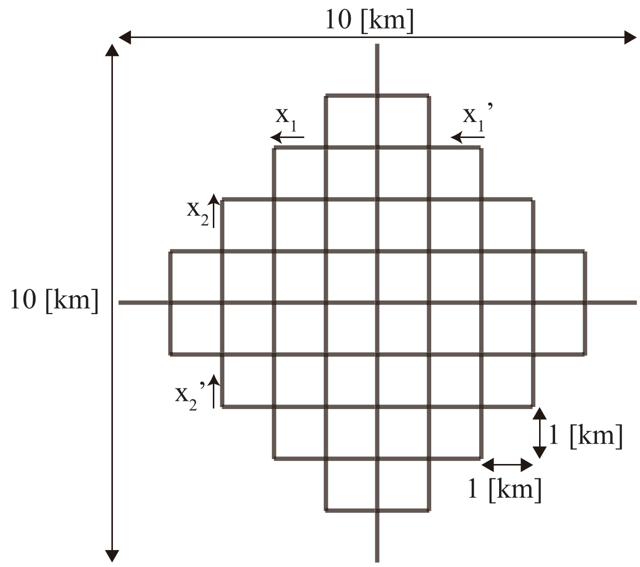

Fig. 3: A two-dimensional road model; the road model is composed of a number of horizontal and vertical roads, each of which has two lanes for each direction.

We use a simple simulation model for investigating the performance of DSCF and P-BCAST. Some simulators [19, 20] with realistic simulation models were developed for performance evaluation of VANET. Such simulators are useful for clarifying performance in realistic environment. Realistic simulation model is too complicated to investigate intrinsic performance of directional transmission. In what follow, we explain the simple simulation model for investigating the intrinsic performance of directional transmission.

To focus the effect of directional property on broadcast communication, we do not consider radio attenuation and collision of message transmission in simulation.

As a two-dimensional road model, we use a well-known Manhattan road model [21] (Fig. 3). Manhattan road model has been commonly used for performance evaluation in VANETs (see, for example, [22, 23]). The road model is composed of a number of horizontal and vertical roads, each of which has two lanes for each direction. A lane means a part of a road, and only has vehicles with a same direction. Simulation of the area more than 5 [km] away from the origin (i.e., the center of the two-dimensional road model) in Manhattan distance [24] is omitted for computational and memory efficiency.

For a given vehicle density ρ [vehicles/km], vehicles are randomly placed on all lanes following a uniform distribution. Each vehicle is assigned a fixed velocity drawn from a normal distribution with the mean of 40 [km/h] and the standard deviation of 5 [km/h]. Similarly to [23], we use a simple fixed-speed and no-turning mobility model for clearly investigating the effect of the epidemic broadcast with directional transmission, rather than the effect of vehicle mobility. Namely, each vehicle moves along the road at a constant velocity, and it makes no turn at intersections.

For fixing the vehicle density during simulation, the number of vehicles is kept constant. Namely, when a vehicle goes outside of the two-dimensional road model, another incoming vehicle is generated at the opposite point. For instance, when a vehicle leaves the simulation area from point x_1, another vehicle is immediately generated at point x'_1. When a vehicle leaves the simulation area from point x_2, another vehicle is immediately generated at point x'_2. At time $t = 0$ [s], a message is generated at the origin, and the epidemic broadcast is initiated.

The Communication ranges is differentiated in DSCF and P-BCAST because of the different energy efficiency in directional and omnidirectional transmission. Namely, we use communication range $R_D = 200$ [m] for DSCF and communication range $R_P = 150$ [m] for P-BCAST. The rationale here is that the communication range with a directional transmission is as approximately $\sqrt{2}$ times as that with an omnidirectional transmission for a fixed energy consumption [25].

In the following simulations, among several system parameters, we particularly focus on the effect of vehicle density ρ [vehicles/km] on performances of DSCF and P-BCAST since the vehicle density ρ is one of the most critical system parameters for epidemic broadcasts [26]. We should note that the effect of other system parameters (i.e., vehicle velocity and the radius of communication range) can be approximately estimated from our simulation results. For instance, doubling the vehicle velocity should have almost the same effect with doubling the simulation speed. Also doubling the radius of communication range should have almost the same effect with doubling the vehicle density.

In all experiments, we repeated 30 simulations and measured the average and 95% confidence interval of all measurements.

B. Performance Metrics

Dynamical behaviors of DSCF and P-BCAST must be investigated instead of their steady-state behaviors since the two-dimensional road model is *open* in a sense that vehicles continuously enter and leave.

There are several simulation studies on epidemic broadcast, and different performance metrics are used in different simulation studies [6, 27, 28, 26]. There is no agreed-upon performance metrics for epidemic broadcasts in VANETs. We use the following time-varying performance metrics in simulation.

- Reachability
  Reachability means how many vehicles can receive a message with broadcast communication. In broadcast communication, it is important to deliver a message to as many vehicles as possible [27]. For instance, road traffic information is required by all vehicles that will pass the message originating point. Therefore, such a message should be delivered to all vehicles, at least, that will pass the message originating point.
  We define *L-coverage(t)* as the ratio of infected vehicles in the area within L [km] away in the Manhattan distance from the origin (i.e., the message originating point) at time t. Thus, 5 [km]-coverage(t) means the ratio of infected vehicles among all vehicles on our two-dimensional road model at time t (see Fig. 3).
- Dissemination speed
  Dissemination speed represents how promptly a message is disseminated with broadcast communication. In broadcast communication, it is usually desirable to deliver information as quickly as possible [28]. The permissible transfer delay is different for message types and their applications [26]. For instance, urgent messages such as notification of car accidents should be delivered to other vehicles as promptly as possible. On the contrary, non-urgent messages such as parking lot information might be delayed to some extent.
  The speed of message dissemination is measured by *p%-delivery_time*, which is defined as the time elapsed until p% of all vehicles successfully receives the message. In our simulations, we focus on, in particular, 50%-, 90%-, and 95%-delivery_time.
- Uniformity
  Uniformity means how uniformly a message is disseminated from the originating point to all directions. In broadcast communication, a message should be disseminated not only along vehicle's forward direction but also toward all radial directions [6]. For instance, road traffic information should be delivered to vehicles on all roads leading to the message originating point. In such a case, broadcast communication biased toward specific direction is not desirable.
  There are several ways to measure the uniformity of message dissemination on two-dimensional road model. We use an intuitive metric called *centroid distance*. Namely, *centroid_distance(t)* is defined as the Manhattan distance of the centroid from the message originating point at time t. The centroid is the central point of all infected vehicle positions. For instance, if the message is equally disseminated in all directions, centroid_distance(t) becomes zero.
- Efficiently
  Efficiency means how efficiently a vehicle-to-vehicle communication is performed. Namely, broadcast communication is efficient if it requires a small amount of communication overhead for a single vehicle-to-vehicle message delivery. The communication overhead used here stands for the number of messages transmitted for making a vehicle to be

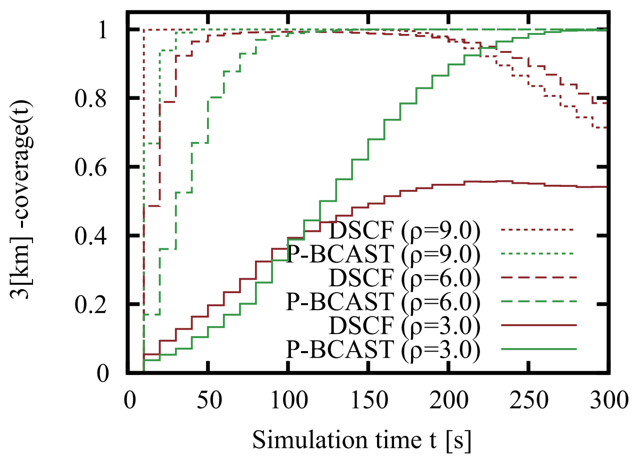

Fig. 4: Evolutions of 3 [km]-coverage(t) in DSCF and P-BCAST for different vehicle densities ρ [vehicles/km]; reachability of DSCF is comparable with that of P-BCAST during several minutes after the epidemic broadcast is initiated.

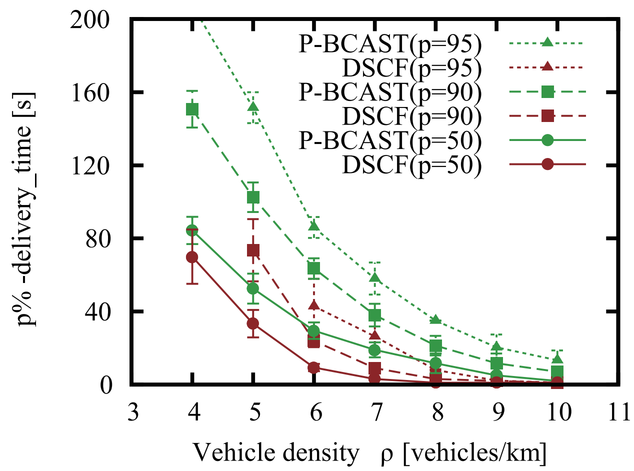

Fig. 5: 50%-, 90%-, and 95%-delivery_time in DSCF and P-BCAST for different vehicle densities ρ; surprisingly, the delivery time in DSCF is considerably shorter than that in P-BCAST regardless of vehicle densities.

infected, for instance. A certain amount of communication overhead is essentially unavoidable in any epidemic broadcast [27, 8]. But if the communication overhead is very high, it results in not efficient communication utilization, leading poor reachability and dissemination speed.

We define *messages_per_delivery(t)* as the average number of messages transmitted for making a vehicle to be infected by time t. More specifically, messages_per_delivery(t) is obtained by dividing the total number of message transmitted in the network by the number of newly infected vehicles at time t. Note that single transmissions from a vehicle to other vehicles within its communication range can be performed with just a single message.

C. Results

- Reachability

  We first measure 3 [km]-coverage(t) in DSCF and P-BCAST for investigating reachability; i.e., how many vehicles can receive a message with epidemic broadcast. Figure 4 shows evolutions of 3 [km]-coverage(t) in DSCF and P-BCAST for different vehicle densities ρ.

  Recall that DSCF is a single-transmission epidemic broadcast while P-BCAST is an infinite-transmission one, and that P-BCAST achieves the optimal reachability, dissemination speed and uniformity while compromising the worst efficiency. Also recall that we are only interested in comparing the short-term behaviors of DSCF and P-BCAST.

  Figure 4 indicates that reachability of DSCF is comparable with that of P-BCAST during several minutes after the epidemic broadcast is initiated. Namely, 3 [km]-coverage(t) in DSCF grows as fast as (or sometimes even faster than) that in P-BCAST. This result implies that, at least in terms of reachability, either such an infinite-transmission mechanism in P-BCAST is not so effective or directional transmission in DSCF is quite effective. In Section V, through mathematically analysis, DSCF achieves good reachability even though it uses directional transmission, which has a limited (narrow) communication range. In both DSCF and P-BCAST, evolutions of 3 [km]-coverage(t) behave quite differently when the vehicle density is very low (i.e., $\rho = 3$ [vehicles/km]). This phenomenon can be explained with the relation between the radius R_D of communication range and the average inter-vehicle distance. More specifically, the average inter-vehicle distance is 333.3 [m] with $\rho = 3$ [vehicles/km], which is larger than the radius R_D of the communication range (i.e., $R_D = 200$ [m] for DSCF and $R_P = 150$ [m] for P-BCAST). In this case, multi-hop message delivery is not likely to happen very frequently, leading very slow message dissemination.
- Dissemination speed

  We then measure 50%-, 90%-, and 95%-delivery_time in DSCF and P-BCAST for investigating dissemination speed; i.e., how promptly a message is disseminated with broadcast communication. Figure 5 shows 50%-, 90%- and 95%-delivery_time in DSCF and P-BCAST for different vehicle densities ρ.

  This figure shows that, surprisingly, the delivery time in DSCF is considerably shorter than that in P-BCAST regardless of vehicle densities. In particular, the delivery time in DSCF is as approximately 50% as that in P-BCAST when the vehicle density is not too low. One possible explanation of this phenomenon is the difference in radiuses of communi-

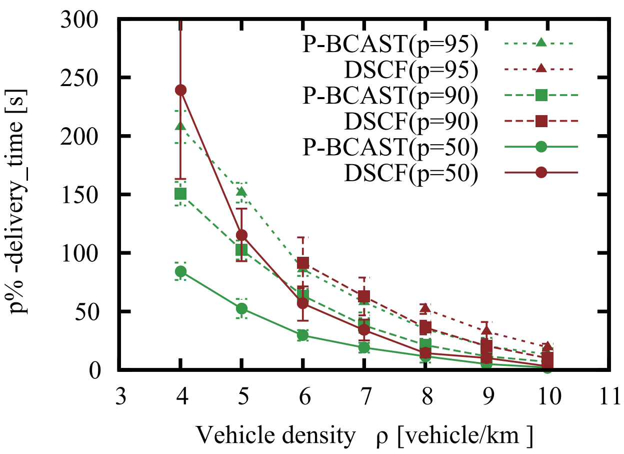

Fig. 6: 50%-, 90%-, and 95%-delivery_time in DSCF and P-BCAST for different vehicle densities ρ; Unlike Fig. 5, the delivery time in DSCF is longer than that in P-BCAST.

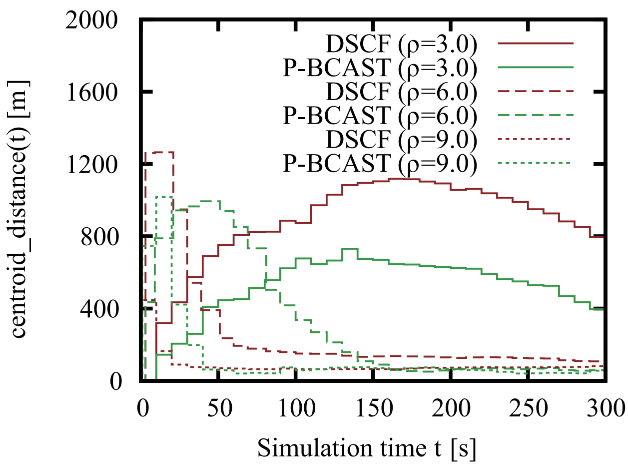

Fig. 7: Evolutions of centroid_distance(t) in DSCF and P-BCAST for different vehicle densities ρ [vehicles/km]; centroid_distance(t) in DSCF is generally as approximately 1.5 times as that in P-BCAST.

cation range (i.e., $R_D = 200$ [m] for DSCF and $R_P = 150$ [m] for P-BCAST).

To clarify why DSCF realizes the shorter delivery time than P-BCAST, we investigate dissemination speed in DSCF and P-BCAST with the same radius of communication range. Figure 5 shows the 50%-, 90%-, and 95%-delivery_time in DSCF and P-BCAST for $R_D = R_P = 150$ [m].

This figure shows that, unlike Fig. 5, the delivery time in DSCF is longer than that in P-BCAST. Hence, by the reason that R_D is larger than R_P, DSCF realize the shorter delivery time than P-BCAST. These results indicate that it is powerful advantage to be able to set large radius of communication range in DSCF.

- Uniformity
  We then measure centroid_distance(t) in DSCF and P-BCAST for investigating uniformity; i.e., how uniformly a message is disseminated from the originating point to all directions. Figure 7 shows evolutions of centroid_distance(t) for different vehicle densities ρ. By definition, the value of centroid_distance(t) itself is intuitive but not very interesting. Instead, we should focus on the relation between centroid_distance(t) in DSCF and that in P-BCAST.
  This figure shows that centroid_distance(t) in DSCF is generally as approximately 1.5 times as that in P-BCAST. This result indicates that the spatial uniformity in DSCF is not significantly deteriorated with introduction of directional transmission. One would expect spatially-biased message dissemination with directional transmission in DSCF. However, as Fig. 7 shows, DSCF achieves acceptable uniformity compared with P-BCAST.
- Efficiency
  We finally measure messages_per_delivery(t) in DSCF and P-BCAST for investigating efficiency; i.e., how efficiently a vehicle-to-vehicle communication is performed. Figure 8 shows messages_per_delivery(t) at t = 50, 100, and 200 in DSCF and P-BCAST for different vehicle densities ρ. Note that messages_per_delivery(t)'s in DSCF are almost identical so that three lines are not distinctive in Fig. 8.
  One can find from this figure that DSCF is quite efficient. Namely, messages_per_delivery(t) in DSCF is always much smaller than that in P-BCAST. Also messages_per_delivery(t) in DSCF increases very slightly as the vehicle density ρ increases. On the contrary, messages_per_delivery(t) in P-BCAST grows quadratically as the vehicle density ρ increases.
  Such a drastic decrease in messages_per_delivery(t)

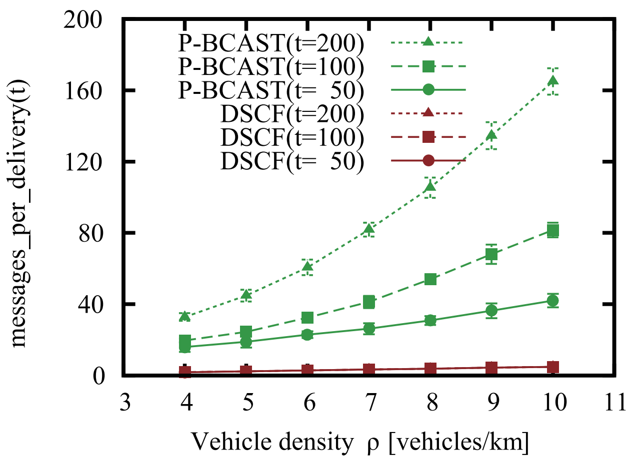

Fig. 8: messages_per_delivery(t) at t = 50, 100, and 200 in DSCF and P-BCAST for different vehicle densities ρ; DSCF is quite efficient.

in DSCF compared with P-BCAST is not surprising. Again, DSCF is a single-transmission epidemic broadcast while P-BCAST is an infinite-transmission one. It is therefore natural that DSCF shows much better efficiency than P-BCAST does. However, it should be emphasized that DSCF achieves comparable (or sometimes even better) reachability and dissemination speed to those of P-BCAST but with significantly better efficiency, which implies favorable characteristics of directional transmission for epidemic broadcasts in VANETs.

V. Consideration with Analysis at an Intersection

We mathematically analyze DSCF to understand the essential property of epidemic broadcasts. In Section IV, we have found that DSCF achieves good reachability even though it performs directional transmission. Through the mathematical analysis, we explain why DSCF achieves good reachability.

In our analysis, without loss of generality, we focus on an intersection in the two-dimensional road (i.e., Manhattan road model) illustrated in Fig. 3. We assume that a vehicle has a message. At the intersection, if the message is frequently transmitted to the orthogonal direction of the vehicle, vehicles in other roads should receive messages, leading to good reachability. Hence, we will derive the probability that the message is sent to either of the orthogonal direction at the intersection.

We use the analytic model illustrated in Fig.9. In Fig. 9, L is the distance between two parallel roads in Manhattan road model. We assume that the radius R_D of communication range is smaller than the distance L. Since we uses Manhattan road model, the vehicle's position between intersections can be denoted by a single variable x $(0 \le x \le L)$ offseted from the previously passed intersection.

In our analytic model, we assume that vehicles are uniformly distributed with the vehicle density ρ [vehicles/km] in all lanes.

In what follows, we derive the probability p_m that the message is sent to either of the orthogonal direction around the intersection. Namely, we derive the probability that the message is transmitted to not only the vehicle's forward direction, but also vehicle's right and/or left directions. Since DSCF transmits the message one time only (i.e., single-transmission), the probability p_m is given by

$$p_m = \frac{1}{R_D}\int_{L-R_D}^{L}\big(1-p_s(x)\big)\,dx, \tag{1}$$

where $p_s(x)$ is the probability that the vehicle conveys or transmits the message in only its forward direction at its position x. The probability $p_s(x)$ is given by

$$p_s(x) = p_f(x)\,(1-p_r(x))\,(1-p_l(x)) + p_{un}(x) \tag{2}$$

where $p_f(x)$, $p_l(x)$, and $p_r(x)$ are probabilities that the vehicle transmits the message in its forward, left, and right directions at the vehicle's position x, respectively. Also, $p_{un}(x)$ is the probability that the vehicle cannot find other vehicles within the sending communication range at the vehicle's position x. The first term in Eq. (2) means the probability that the vehicle can only transmit other vehicles for its forward direction within the sending communication range.

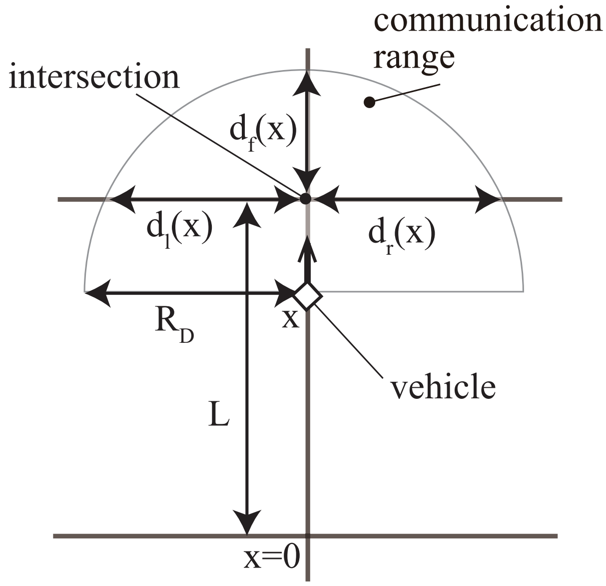

Fig. 9: Analytic model

In what follows, we derive the probability $p_{un}(x)$ that the vehicle cannot find other vehicles within the sending communication range at the vehicle's position x as a limiting case of discrete road model where roads are divided into cells with the length Δ. First, we derive the probability $p_{un}^{(d)}(k)$ that vehicles does not find in all cells within the sending communication range at the vehicle's discrete position k $(0 \le k\,\Delta \le L)$. If the cell length Δ is sufficiently small and at most one vehicle exists in a cell, the probability that a vehicle exists in a cell is approximately given by $\rho\,\Delta$. We assume that the vehicle can find another vehicle in a cell if another vehicle exists in the cell. By using these approximation and assumption, the probability $p_{un}^{(d)}(k)$ at the vehicle's discrete position k is given by

$$p_{un}^{(d)}(k) = (1-\rho\,\Delta)^{\frac{d_f(k)+d_l(k)+d_r(k)}{\Delta}}, \tag{3}$$

where $d_f(x)$, $d_l(x)$, and $d_r(x)$ are lengths of road segments covered by the sending communication range in forward, left, and right directions at the vehicle's position x, respectively, illustrated in Fig. 9. The lengths $d_f(x)$, $d_l(x)$, and $d_r(x)$ are given by

$$d_f(k) = \begin{cases} k\Delta + R_D - L & \text{if } L - R_D \le k\Delta \le L \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

$$d_l(k) = d_r(k) = \begin{cases} \sqrt{R_D^2 - (L-k\,\Delta)^2} \\ \qquad \text{if } L - R_D \le k\Delta \le L \\ 0 \ \text{otherwise} \end{cases} \tag{5}$$

By $\Delta \to 0$ in Eq. (3), the probability $p_{un}(x)$ that the vehicle cannot find other vehicles within the sending communication range at the vehicle's position x is given by

$$\begin{aligned} p_{un}(x) &= \lim_{\Delta \to 0} (1 - \rho\,\Delta)^{\frac{d_f(k)+d_l(k)+d_r(k)}{\Delta}}, \\ &= e^{-\rho\,(d_f(x)+d_l(x)+d_r(x))}. \end{aligned} \quad (6)$$

By using the same way of derivation for the probability p_{un}, probabilities $p_f(x)$, $p_l(x)$, and $p_r(x)$ at the vehicle's position x are given by

$$p_f(x) = 1 - e^{-\rho\,d_f(x)}, \quad (7)$$
$$p_l(x) = 1 - e^{-\rho\,d_l(x)}, \quad (8)$$
$$p_r(x) = 1 - e^{-\rho\,d_r(x)}. \quad (9)$$

By substituting Eqs.(2) through (9) into Eq.(1), we obtain

$$p_m = \frac{1}{R_D} \int_{L-R_D}^{L} \left(1 - e^{-\rho\,(d_l(x)+d_r(x))}\right) d\,x. \quad (10)$$

Through numerical examples of our analysis, we investigate the reachability of DSCF. We perform simulation with the road model with one intersection and two roads for comparing analysis results with simulation ones. In analysis and simulation, we use the parameter setting $L = 1$ [km] and $R_D = 200$ [m]. In simulation, at time $t = 0$ [s], a message is generated at the $x = 0$, and the epidemic broadcast is initiated. For other simulation setup, we use the simulation setup explained in Section IV-A. As a counterpart to the probability p_m in simulation, we calculate the ratio r_m given by

$$r_m = \frac{N_m}{N_s}, \quad (11)$$

where N_m is the number of simulations in which a message is sent to either of the orthogonal direction at the intersection, and N_s is the number of performed simulations. By comparing the probability p_m and the ratio r_m, we investigate the difference between our analysis and simulation.

Figure 10 shows that the probability p_m and the ratio r_m for different vehicle densities ρ obtained from analysis and simulation, respectively. From Fig. 10, the probability p_m decreases as the vehicle density ρ decreases. However, when the vehicle density ρ is low (i.e. $\rho = 3$ [vehicles/km]), DSCF keeps more than 0.5 of the probability p_m, leading to good reachability of DSCF shown in Section IV. From Fig. 10, analysis results give close agreement with simulation ones. Therefore, there is not much the difference between our analysis and simulation.

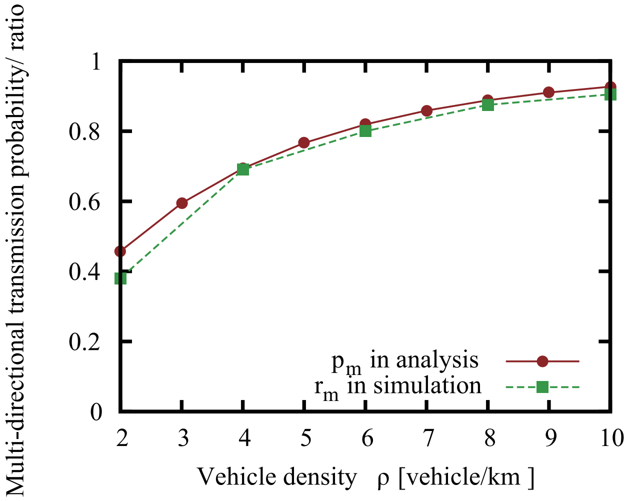

Fig. 10: Probability p_m and ratio r_m for different vehicle densities ρ

VI. Conclusion

In this paper, we have extensively investigated the effectiveness of DSCF in terms of *reachability, dissemination speed, uniformity, and efficiency*. The performance of DSCF has been thoroughly compared with that of P-BCAST. According to our findings, we conclude that DSCF can achieve satisfactory reachability and dissemination speed comparable to those of P-BCAST with significantly better efficiency, which implies favorable characteristics of directional transmission for epidemic broadcasts in VANETs. Finally, we have mathematically analyzed DSCF to understand the essential property of epidemic broadcasts.

As future work, we are planning to investigate the impact of the division number of communication range in directional transmission on the performance of DSCF, and clarify the optimal division number of communication range in directional transmission for DSCF. Moreover, we are planning to investigate directional transmission on epidemic broadcasts in VANETs by using a realistic road model and vehicle mobility model.

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