Fast Message Broadcasting in Vehicular Networks: Model Analysis and Performance Evaluation

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***Abstract*—The pervasive use of technology in the urban environment requires evolved algorithms able to deliver messages across vehicular ad-hoc networks (VANETs). These networks could be exploited to run a vast plethora of applications, including critical ones such as emergency message distribution. The state-of-the-art broadcasting solutions are based on providing vehicles with different probabilities of forwarding the message in order to reduce message collisions and the number of hops to cover a certain area of interest. In this article, we examine a class of these propagation algorithms, discussing their model analysis and performance evaluation. Furthermore, we propose a possible algorithm's extension introducing a dynamic setting of parameters according to the vehicular network's conditions.**

***Index Terms*—Vehicular networks, multi-hop communication, network optimization, safety**

I. Introduction

VEHICULAR networks are certainly becoming of global interest, considering the recent trends in self-driving, safety, mobile entertainment/infotainment, vehicular intelligence and other kinds of service. One of the major challenges for these networks is message broadcasting (e.g., for alert message distribution), which relies on diverse solutions able to efficiently deliver a message [1], [2], [3], [4].

Recent research results [5], [6], [7], [8] have demonstrated that the broadcast time of a message within a vehicular network is strictly related to the number of message relays (hops) and the network congestion. To reduce broadcasting time, a solution requires information on vehicles' positions and a careful choice of the algorithm's parameters.

Generally, fast message broadcasting in vehicular networks leverages on a specific class of solutions, characterized by the following properties [9]:

- Vehicle-to-Vehicle (V2V) communication, without infrastructure;
- position, direction, speed, and other information exchange;
- multi-hop propagation over an Area of Interest (AoI);
- selection of as few forwarders as possible, through a specific mechanism for channel contention.

Within this class fall solutions such as those presented in [8], [10], [11], [12]. In each of them, the proposed algorithm tries to elect the smallest possible set of nodes as forwarders by privileging, at every hop, the farthest node (or similar, e.g., the node with the farthest span) within the transmission range to become the next forwarder of the message.

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The Fast Multi-hop Broadcast Algorithm (FMBA) is a representative state-of-the-art protocol, which shares the aforementioned properties [12]. FMBA is designed for rapid message propagation over a vehicular platoon; it aims at reducing the number of hops traversed by a message to minimize its propagation delay. To do so, different contention windows are assigned to vehicles receiving the broadcast message in order to become the next forwarder; the aim is to privilege farthest vehicles in the transmission range to take care of the message propagation on the next hop so as to reduce the number of hops and the total time required to cover a certain AoI.

Clearly, the range of values that can be used as contention window embodies a main factor in determining the performance of the system. To this aim, we assess through analytical and simulation-based evaluation the impact of different settings for the contention window depending on the density of vehicles. As a further contribution, we show how analytical results can be practically employed to improve the performance of FMBA and, in general, of its class of solutions.

II. The Fast Multi-hop Broadcast Algorithm

FMBA is aimed at fast multi-hop propagation of alert messages in vehicular networks [12]. The considered scenario is comprised of vehicles with V2V communication capabilities supporting alert message broadcasting over a certain AoI. Through *hello messages*, vehicles exchange information about their position and compute an estimation of their transmission range. This information is then used in the case of an emergency to determine message forwarding criteria so as to prioritize vehicles with the farthest reach from the source in becoming the next forwarders of the alert message in the AoI.

To make things clearer, we can consider the example depicted in Fig. 1, where vehicle A is involved in an accident. With FMBA, the farthest vehicle(s) from the current sending one will have higher chances to become the next forwarder(s), thanks to a smaller contention window assigned by the algorithm to the farthest vehicles in the transmission range. As a result, AoI coverage is achieved with the minimum number of hops. In the example, the ideal candidate forwarding path

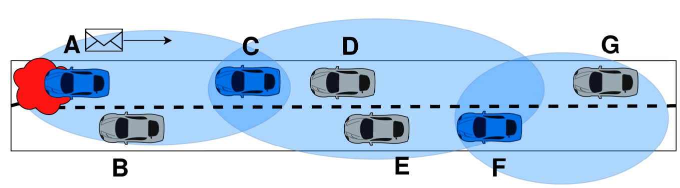

Fig. 1. Multi-hop forwarding; ellipses denote the estimated backward transmission ranges of blue vehicles (the message forwarders).

is comprised by vehicles C and F. To improve the resiliency of the system, if one of these vehicles gets disconnected before receiving or forwarding the message, then the second farthest one will perform the task, and so on. In any case, when a node forwards the message, vehicles between the previous and the current forwarder will stop their forwarding countdown/attempt, whereas all nodes receiving the forwarded message at a farther distance from the source will reset their mechanism for channel contention on the next hop.

More in detail, FMBA can be in two phases: (i) estimation phase and (ii) forwarding phase. The goal of the former is to make all vehicles aware of their transmission range so as to be able to use this information during a potential forwarding phase. Then, during the forwarding phase, forwarding vehicles include their transmission range estimation in the alert message and this information is then used by recipient nodes to assign themselves a contention window size (cws), defined as a number of time slots that determines their likelihood in becoming the next forwarder.

When a vehicle sends an alert message, the vehicles in the sender's transmission range are denoted by I and each $i \in I$ computes its contention window $[1, cws(i)]$, with $cws(i)$ set to a value in the range between two constants $\underline{cws}$ and $\overline{cws}$ (the lower bound and the upper bound, respectively) depending, in a proportional way, on the ratio between their distance from the sender and the transmission range [12]:

$$cws(i) = \left\lfloor \overline{cws} - \frac{d(i)}{range} \left(\overline{cws} - \underline{cws} \right) \right\rfloor \tag{1}$$

In (1), $d(i)$ is i's distance from the sender, $range$ is the sender's estimated transmission range, $\overline{cws}$ and $\underline{cws}$ are given values measured in time slots (simply named $slots$ from now on, for the sake of conciseness) as done for regular contention windows in classic MAC protocols. Successively, each vehicle $i \in I$ randomly selects its waiting time, in terms of slots within $[1, cws(i)]$, generating a waiting time (slots) u_i as an occurrence for the random variable U_i uniformly distributed in the integer set $\{1, \ldots, cws(i)\}$. At the end of such waiting time u_i, vehicle i will try to forward the message, if no other vehicle already did it. Consequently, the forwarder will be the fastest vehicle in transmitting the message, that is the one in I that has generated the smallest number of slots as its cws, if this smallest number is unique.

Otherwise, when the minimum number of slots $\min_{i \in I} u_i$ is generated by two or more vehicles then the multiple, simultaneous message transmissions cause a message collision and another forwarder will be determined very few slots (even just one) later.

Generally, by trying to create longer hops through a specifically selected forwarder, a protocol increases the risk of failure due to unpredictable disconnection of the selected forwarder. Instead, with FMBA, if the vehicle computing the smallest cws gets disconnected, it will just not take part in the forwarding procedure; one of the other (connected) vehicles will forward the message as all vehicles are enabled to forward the message until someone else in the transmission range does it first (silencing the others).

III. Analytical Model

Since FMBA aims to minimize the propagation delay of a message, the time taken by a single hop needs to be short and each hop needs to be as long as possible.

The duration of a hop depends on the random variable $Z = \min_{i \in I} U_i$ and on the probability that a collision occurs. The independence of random variables U_i's implies that

$$P[Z \geq z] = \prod_{i \in I} P[U_i \geq z] = \prod_{i \in I} \frac{cws(i) - z + 1}{cws(i)} \tag{2}$$

and the average value of Z can be computed by

$$\begin{aligned} E\left[Z\right] &= \sum_{z=1}^{\min_{t \in I} cws(t)} P[Z \geq z] \\ &= \sum_{z=1}^{\min_{t \in I} cws(t)} \left(\prod_{i \in I} \frac{cws(i) - z + 1}{cws(i)} \right). \end{aligned} \tag{3}$$

The probability of a collision occurring is

$$P\left[Collision\right] = 1 - \sum_{k \in I} p_k, \tag{4}$$

where p_k is the probability that the waiting time of vehicle k is strictly less than the waiting time of any other vehicle and can be computed through the following steps:

$$\begin{aligned} p_k &= P\left[U_i > U_k \text{ for all } i \in I \setminus k\right] \\ &= \sum_{j=1}^{cws(k)} P\left[U_i > U_k \text{ for all } i \in I \setminus k \mid U_k = j\right] \cdot P\left[U_k = j\right] \\ &= \frac{1}{cws(k)} \cdot \sum_{j=1}^{\min_{t \in I} cws(t)} \left(\prod_{i \in I \setminus k} \frac{cws(i) - j}{cws(i)} \right). \end{aligned}$$

Finally the expected duration of a hop is given by

$$\frac{E\left[Z\right]}{1 - P\left[Collision\right]}. \tag{5}$$

The probability that a fixed vehicle k is the forwarder can be obtained through $p_k/(1 - P[Collision])$. The length of a hop is a discrete random variable whose values are the distances of any vehicle k from the sender and the associated probability is equal to the probability that vehicle k is the forwarder. The average value of such random variable gives the expected length of a hop.

IV. Analytical Outcome and Validation

We consider a scenario similar to the one in [7], having a platoon of vehicles on a strip-shaped road. To maintain the generality of results we use meters (m) as unit of measure, allowing it to be proportionally changed without altering the final results. Adopting an actual transmission range of 1000 m for each vehicle, we performed FMBA using different $(\underline{cws}, \overline{cws})$ couples, whose values are:

- $\overline{cws} = \{64, 128, 256, 512, 1024\}$
- $\underline{cws} = \{8, 16, 32, 64\}$.

To appreciate the behavior of FMBA under different platoon densities, we adopted several vehicles numbers per range, from 25 to 400, with steps of 25.

TABLE I
ANALYTICAL OUTCOMES WITH 100 VEHICLES PER RANGE.

$(\underline{cws}, \overline{cws})$	(8, 64)	(16, 128)	(16, 256)	(32, 512)	(64, 1024)
$P[Coll]$	0.92	0.67	0.48	0.26	0.14
$E[Z]$	1.02	1.17	1.43	2.23	3.90
ExpDur	12.73	3.51	2.73	3.03	4.53

For each configuration instance, we analytically computed the average duration of a single hop (measured in slots) and the average geometrical length of a hop (the distance between the sender and the next forwarder).

To better appreciate the tradeoff related to the contention window size, we consider here a representative example with 100 vehicles per range and report in Table I the corresponding values of $P[Collision]$, $E[Z]$ and the expected duration of a hop for some possible $(\underline{cws}, \overline{cws})$ couples. Even with these few values it is clear how the probability of a message collision increases with the number of vehicles, thus causing waste of time slots before actually forwarding it, while the average minimum slot chosen decreases with larger vehicle volumes. Choosing the best $(\underline{cws}, \overline{cws})$ couple depending on the current vehicle volume is hence crucial to ensure the lowest possible expected hop duration.

To validate the analytical results, we conducted a set of simulations, performing 500 runs for each instance. We have chosen the latest version of the Network Simulator 3 (ns-3), which supports realistic wireless network characteristics. We configured our simulation testbed as similar as possible to the network conditions considered by the papers describing FMBA and, in general, the state-of-the-art literature (i.e., the Constant Speed Propagation Delay model and the Two-Ray Ground Propagation Loss model). Furthermore, we defined the MAC and PHY modules conform to the IEEE 802.11 standard. As the system is focused on the transmission slot chosen by vehicles to forward very small messages, with very limited bandwidth consumption, the outcome is independent from the underlying MAC standard - 802.11b/g/n/p...

In the simulations, we considered two cases of vehicles distribution: in the former vehicles are uniformly distributed along the road, in the latter they obey a Poisson process distribution. Since results are very similar, for the sake of conciseness, we report in the paper only the latter case.

Both analytically and via simulations, the average length of a hop turns out to be about 750 m in each instance, that is $3/4$ of the transmission range, with minor and negligible variations. Hence, we can focus just on a single hop as on each hop the process repeats itself independently.

For any considered number of vehicles per transmission range in the first column, Table II reports: in the second column, the $(\underline{cws}, \overline{cws})$ couple that analytically minimizes the average duration in slots of a single hop as given by (5); in the third column, the corresponding minimum average duration of a single hop; in the last one, the related simulation-based average hop duration for the same $(\underline{cws}, \overline{cws})$ couple.

As expected, with a low number of vehicles contending the channel, the probability of collision is low too; hence, $\underline{cws}$ and $\overline{cws}$ can be small without significantly affecting the collision probability. This improves the efficiency of the system, as if higher values were chosen, the expected hop duration would be bigger. On the contrary, with high vehicle density, the probability of collision increases; as shown in Table II, the minimum duration of a hop for high densities of vehicles is obtained for higher cws sizes.

TABLE II
ANALYTICAL AND SIMULATION-BASED EXPECTED DURATION RESULTS.

Vehicle Volume	$(\underline{cws}, \overline{cws})$	Analytic	Simulation
25	(8, 64)	2.64	2.68
50	(16, 128)	2.68	2.71
75	(8, 256)	2.68	2.76
100	(32, 256)	2.70	2.82
125	(16, 512)	2.71	2.79
150	(16, 512)	2.70	2.73
175	(32, 512)	2.71	2.60
200	(64, 512)	2.71	2.64
225	(16, 1024)	2.70	2.92
250	(16, 1024)	2.70	2.70
275	(32, 1024)	2.71	2.79
300	(32, 1024)	2.71	2.75
325	(64, 1024)	2.71	2.62
350	(64, 1024)	2.71	2.94
375	(64, 1024)	2.72	2.62
400	(64, 1024)	2.75	2.72

In conclusion, we carried out a comparison between the average duration of a single hop in our analytical model (column *Analytic*) and in ns-3 simulations (column *Simulation*), obtaining very similar results. The shown data validate our analytical results, hence observing preferable cws sizing according to the number of vehicles in transmission range.

V. A DYNAMIC SOLUTION WITH ADAPTIVE PARAMETERS

We propose a dynamic approach, where the vehicular density is taken into account to properly set the $\underline{cws}$ and $\overline{cws}$ parameters, in order to reduce the transmission time.

To measure the number of vehicles in a transmission-size area, vehicles can exploit the presence of hello messages. Generally, hello messages are expected to be generated by each vehicle every 100 ms (clearly with a random component to avoid synchronization and subsequent message collisions) [10], [12]. We have chosen to use the same period in our tests although different periodicity could be used (e.g., a dynamic one that widens the period when the number of vehicles around exceeds certain thresholds). Nodes count how many different sources of hello messages have been detected to determine the cardinality of the set of neighbours. If a node is not detected for a certain amount of time (e.g., 3 periods in our tests), that node is removed from the considered set of neighbours.

The cardinality of the current set of neighbours is then used in the case an alert message has to be forwarded. Basically, the current neighbour set cardinality is compared with the values in the *Vehicle Volume* column of Table II and the entry with the closest value is chosen. The corresponding $\underline{cws}$ and $\overline{cws}$ values are then included in the forwarded alert message, along with the other classic information suggested by FMBA (e.g., forwarder's position and transmission range estimation, alert type, etc.) so that the recipient vehicles correctly set these parameters when applying (1).

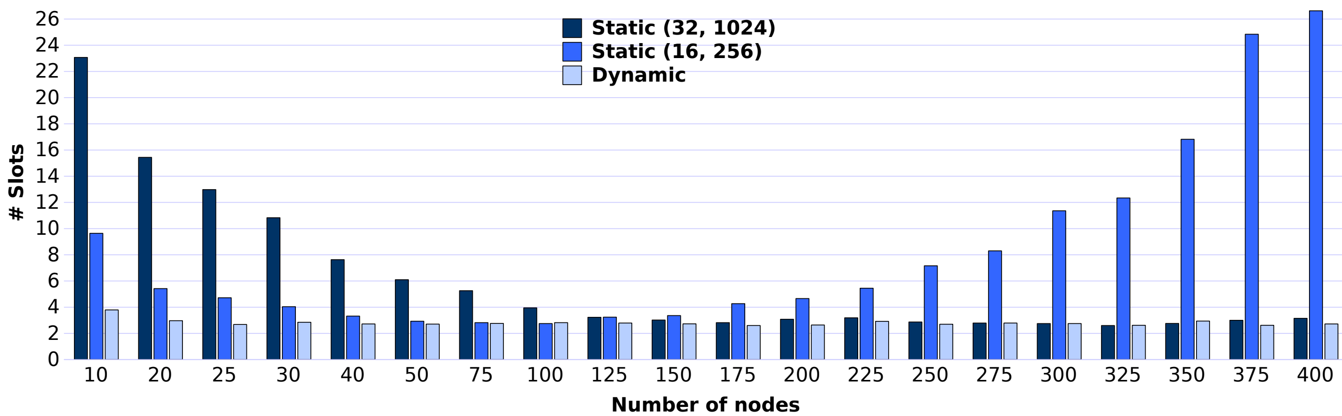

Fig. 2. Expected hop duration comparison considering the dynamic FMBA algorithm and two static ones.

VI. Comparing static and dynamic solutions

In Fig. 2 we compare two static solutions (with fixed $\underline{cws}$ and $\overline{cws}$ values for each vehicle density) against the dynamic one (which selects the values of the cws parameters according to Table II). The simulated configurations vary in terms of the number of vehicles within the transmission range area. As expected, having static cws values causes a significant increase of the hop's duration in adverse configurations. In particular, low cws values, e.g., *Static (16, 256)*, lead to a long hop duration for high vehicle volumes. In this case, the collision probability increases, as a high number of vehicles must rely on few available slots. On the other hand, high cws values, e.g., *Static (32, 1024)*, lead to a long hop duration for low vehicle volumes as the probability to select a large number of slots increases with $\overline{cws}$ increasing.

Beside the hop duration, other metrics that could be considered are *reachability* and *saved rebroadcast* [13]. The former is related to the percentage of vehicles in the transmission range that receives a transmission, whereas the latter regards the ratio between the non-forwarding vehicles receiving the message and the total amount of vehicles. However, considering our solution, investigating these metrics is quite trivial for three reasons. First, one and only one vehicle eventually forwards the message with success. Second, all vehicles in the transmission range receive it as we have deliberately avoided shadowing areas in our simulations to gather clearer results regarding the impact of the contention windows on the hop duration. Third, message collisions are very rare thanks to the selection of the appropriate contention windows. Consequently, our solution achieved a value very close to 1 (the best case) for both these metrics in all simulated scenarios.

VII. Conclusion

In this paper, we have focused on a class of solutions for fast message broadcasting in vehicular networks, discussing a model analysis and a performance evaluation. Furthermore, focusing on FMBA as a representative example of this class of solutions, we have proposed an improvement based on the outcome of our analysis. Our solution is able to dynamically set contention window parameters according to the vehicular network's conditions in order to provide low broadcasting time.

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