MAC Contention Distributions for Efficient Geo-routing in Vehicular Networks

Carolina García-Costa, Esteban Egea-López and Joan García-Haro
Department of Information and Communication Technologies,
Universidad Politécnica de Cartagena (UPCT), Spain,
e-mail: {carolina.garcia, esteban.egea, joang.haro}@upct.es.

***Abstract*—In this paper we evaluate a MAC-layer contention-based forwarding scheme for vehicular networks that prioritizes access according to node position. In particular, we consider two schemes that use a geometrically-increasing probability distribution for choosing the contention slots but, in the first case, the distribution is appropriately weighted, and in the second case, vehicles select the window size according to their position. We analytically evaluate the total and per-vehicle success probabilities and the average delay bounds. Our results show that a weighted geometric distribution effectively prioritizes the access based on position for a wide range of vehicle densities, while retaining the benefits of geometrical distributions with respect to success probabilities and delay bounds.**

***Index Terms*—Vehicular networks, geo-routing, contention-based forwarding, MAC slot distribution**

I. Introduction

Inter-vehicle communications based on wireless technologies pave the way for innovative applications in traffic safety, driver-assistance, traffic control and other advanced services which will make up future Intelligent Transportation Systems (ITS) [1]. Communications for Vehicular Ad-Hoc Networks (VANET) have been developed and standardized in the last years. At the moment, a dedicated short range communication (DSRC) bandwidth has been allocated to vehicular communications at 5.9 GHz and both American and European standards [2] have adopted IEEE 802.11p as physical and medium access control (MAC) layers, based on carrier-sense multiple access with collision avoidance (CSMA/CA).

At the network layer, European standards [3] specify the GeoNetworking protocol as the default network layer protocol for vehicle-to-vehicle (V2V) communications. It provides packet routing based on the use of geographical positions, that is, a geo-routing protocol. GeoNetworking (GeoNet) supports the communication among individual ITS stations as well as the distribution of packets in geographical areas. If the source node does not belong to the destination geo-area, then the packet should be forwarded until reaching a node which belongs to this area, which takes care on delivering the packet to its destination. As basic forwarding algorithms, [3] defines greedy forwarding and contention-based forwarding (CBF) [4]. The latter makes a receiver decide if it becomes the next forwarder, according to its position. Upon receiving a packet, all routers start a timer whose timeout depends on the specific position of the router, usually inversely proportional to the distance. The major advantage of CBF is that it provides an implicit reliability mechanism in case the most suitable router does not receive the packet, which in such a highly dynamic environment is quite likely. Contention-based forwarding may be implemented at network layer or directly at the MAC layer.

Implementing CBF at MAC layer should result in lower delays than network layer operation, since forwarding and access delays are integrated. Moreover, CSMA/CA mechanisms can be controlled with several parameters, like contention window size and intervals as well as the probability distribution for the slot selection, which results in multiple degrees of freedom to optimize MAC operation according to the most critical functionality offered by the network. For instance, such an optimization should benefit safety and emergency related applications which rely and are built on top of the functionality of the geo-routing protocol. As drawback, implementation at the MAC layer may be potentially more complex, requiring at least firmware modification.

CBF operation synchronizes medium access of all nodes, that is, all receivers of a packet immediately become potential forwarders and contend for the medium. In this particular situation, in [5] it is shown that there exists an optimal distribution for the contention slots that maximizes the contention success probability. Although the optimal distribution cannot be implemented in practice, geometric distributions approximate the optimal one. With such a distribution the conditional access probability in case of success is uniformly distributed among all the contenders. However, the main goal of CBF is to prioritize the access of the most suitable node according to its position. Therefore, our objective is to find a mechanism that prioritizes access based on position while retaining the good properties of geometric distributions.

The remainder of this paper is organized as follows. In Section II we briefly review the related work. A MAC-layer CBF scheme that prioritizes access according to node position is proposed in Section III. In Section IV we analytically evaluate the total and per-vehicle success probabilities and the average delay bounds. Finally, conclusions and future work are remarked in Section V.

II. Related Work

Because of the dynamic nature of the mobile nodes in the network, finding and maintaining routes is very challenging in VANETs. Routing in VANETs (with pure ad hoc architectures) has been studied recently and many different protocols have been proposed. The authors in [6] classify them into five categories as follows: ad hoc, position-based, cluster-based, broadcast and geocast routing.

The objective of a geocast routing [7] is to deliver the packet from a source node to all other nodes within a specified geographical region. Most geocast routing methods are based on directed flooding, which tries to limit the message overhead and network congestion of simple flooding by defining a forwarding zone and restricting the flooding inside it. Non-flooding approaches are also proposed [8], [9], aiming to limit the number of concurrent packets within the network.

We are particularly interested in the methods that use the contention scheme at the MAC layer to select the next forwarding node. This is achieved either by adapting the time when to forward the packet or by introducing rules on whether a given vehicle should forward the packet at all as in [4]. If CSMA/CA is used at the MAC layer, not only the contention window size may be selected [10] but also the distribution function used for the selection of the contention slots may be specifically adapted [5]. In this paper, we use the latter approach, adapting the method in [5] not only to reduce the message overhead, but to prioritize the retransmission of the packet by certain nodes (e.g. the farthest node).

III. Adaptations of Sift for Prioritized Access

Sift is the contention technique proposed in [5] for event-driven networks where a set of nodes tries to send a packet *simultaneously*. That is, when there are synchronized channel access attempts among many nodes. The key idea in Sift is to use a non-uniform, geometrically-increasing probability distribution for choosing the slots $(1, \dots, CW)$ within a fixed-size contention window (CW), rather than varying the window size as in many traditional MAC protocols. The resulting protocol performs well when the number of nodes trying to send data is large in relation to CW, therefore it scales well when the number of contenders grows.

The Sift protocol assigns the probability that a node chooses the slot r as :

$$p_{CW}(r) = \frac{(1-\alpha)\alpha^{CW}}{1-\alpha^{CW}} \cdot \alpha^{-r}, \quad r = 1, \dots, CW, \tag{1}$$

where $0 < \alpha < 1$ is a characteristic coefficient that determines the shape of the probability distribution.

Let us note that using CBF for GeoNet implies that all the packets are broadcast. In this mode, there is no reliability mechanisms, such as acknowledgment packets, and every transmission is independent of each other. In addition, all receiving nodes become simultaneously potential forwarders (contenders) *simultaneously*. When a node wins the contention, it rebroadcasts the packet and the process is exactly the same, and actually keeps on this way until the packet reaches the destination area.

Therefore, we might expect that Sift as contention distribution optimize the operation of GeoNet hop by hop. However, with the Sift distribution, all the vehicles use the same distribution for the slot selection, so all of them have the same probability of success in accessing the channel. On the contrary, for many applications in VANETs it is needed that certain vehicles have a success probability greater than the rest of them. A clear example is the usual GeoNet scenario described in Section I, where the node located farthest away should have priority access. In summary, our purpose is to design a protocol that assigns higher success probability to the nearest node to the destination, but without decreasing the total success probability. This is achieved by allowing that each vehicle uses a different probability distribution for the slot selection, based on its own position. Next we propose variations of Sift that retain its benefits but adapting the operation to the needs of the GeoNet protocol.

A. Weighted Sift

The first method we propose is to weight the Sift distribution according to the respective position of vehicles within the transmission range of the source node, giving a higher success probability to the farthest nodes.

Considering the number of contending vehicles equal to N, each one of these vehicles, $i \in \{1, \dots, N\}$, will choose the slot $r \in \{1, \dots, CW-1\}$ with probability

$$g_{CW}(i,r) = \gamma_i \cdot p_{CW}(r), \tag{2}$$

while the probability of vehicle i choosing slot CW is

$$g_{CW}(i, CW) = 1 - \gamma_i \sum_{r=1}^{CW-1} p_{CW}(r), \tag{3}$$

where p_{CW} is the Sift probability distribution over CW slots, as defined in eq. (1).

The following step is to select properly the coefficients γ_i, with the condition that them should be bigger for the farthest vehicles. Since the $g_{CW}(i,r)$, $r \in 1, \dots, CW$, constitutes a probability distribution, the sum of the first $CW - 1$ probabilities should be less than 1. From this observation we obtain $\gamma_i \leq 1/\sum_{r=1}^{CW-1} p_{CW}(r)$.

Let us define

$$\gamma_i = w_i \cdot \left(\sum_{r=1}^{CW-1} p_{CW}(r) \right)^{-1}, \tag{4}$$

with $w_i \in (0,1)$ for $i \in \{1, \dots, N\}$.

In order to assign higher values of w_i to the farthest vehicles we use the following inverted and truncated exponential distribution:

$$w_i = 1 - \frac{G(R - x_i)}{G(R)}, \tag{5}$$

where R denotes the transmission range of the source node, x_i the position of vehicle i in R (with respect to the source node) and finally G denotes the cumulative distribution function of an exponential distribution[1]. Let us remark that knowning the exact number of contenders is not required for this procedure.

[1]In this work an exponential distribution with mean $R/3$ is used, but its choice is quite arbitrary. We leave as future work the study of the most appropriate parameters.

B. Per groups Sift

The second method we consider is to divide the total number of vehicles into different groups, depending on their priorities. In particular, as we assume the priority is given by the position, we divide the transmission range into C intervals. The group of vehicles placed in each of these intervals selects their contention slots by using the Sift probability distribution with different values for the contention window (lower values for higher priorities).

Therefore, to each group of vehicles $G_j,\ j \in \{1,\ldots,C\}$, we associate a contention window CW_{G_j}. So, the probability distribution used by all the vehicles in that group is the following:

$$h_{CW_{G_j}}(r) = p_{CW_{G_j}}(r), \quad r \in \{1,\ldots,CW_{G_j}\}, \tag{6}$$

where $p_{CW_{G_j}}$ is the Sift probability distribution over CW_{G_j} slots, as defined by eq. (1).

IV. Comparative Evaluation

In this section we present a comparative study to show the performance of the proposed methods as forwarding algorithms.

We consider a one-dimensional scenario in which vehicles are uniformly distributed. The transmission range is assumed to be constant and equal to 300 meters for all the vehicles, and each vehicle knows its own position in the road segment. We assume that after a first transmission of the packet from the source node, all the vehicles in the transmission range have received correctly the packet and all of them contend to be the next forwarder.

We are concerned here exclusively with the probability of success of the proposed distributions, rather than the actual reception probability, which also depends on fading and channel error. We only need to know the total number of contenders and their positions for the analytic computations. In fact, a real implementation of the proposed protocols only would require to approximately know the transmission range and that each vehicle would know its own position.

A. Performance metrics

Assuming that there are N vehicles contending to be the next forwarder, and that the size of the contention window is CW, for each protocol we construct a matrix $\mathbf{P}$ of dimension $N \times CW$, where $\mathbf{P}(i,j)$ is the probability of node i selecting backoff value j. Then, using this probability matrix, we compute the following stochastic metrics.

The probability of a successful transmission (of any node) in the slot S_r is calculated as the sum of the probabilities that one node selects slot r and the $N-1$ remaining nodes do not choose slots from the range of $1,\ldots,r$, which is given by the expression:

$$\Pi_{S_r}(\mathbf{P}) = \sum_{i=1}^{N} \mathbf{P}(i,r) \prod_{j=1, j\neq i}^{N} \left(1 - \sum_{s=1}^{r} \mathbf{P}(j,s)\right). \tag{7}$$

The probability of a successful transmission for an arbitrary vehicle V_i (in any slot) is calculated as the sum of the probabilities that the node selects one slot and all the other $N-1$ nodes choose later slots, which is given by the expression:

$$\Pi_{V_i}(\mathbf{P}) = \sum_{r=1}^{CW-1} \mathbf{P}(i,r) \prod_{j=1, j\neq i}^{N} \left(1 - \sum_{s=1}^{r} \mathbf{P}(j,s)\right). \tag{8}$$

Immediately from eq. (8) we can compute the probability of a successful transmission for the last group of vehicles and the total probability of a successful transmission as follows:

$$\Pi_{LG}(\mathbf{P}) = \sum_{i \in LG} \Pi_{V_i}(\mathbf{P}) \tag{9}$$

$$\Pi_T(\mathbf{P}) = \sum_{i=1}^{N} \Pi_{V_i}(\mathbf{P}), \tag{10}$$

where LG is the last group of vehicles, that is, the nearest group of vehicles to the destination.

Additionally, we compute the mean winner vehicle (veh^*) and the mean slot number (sl^*) in which the successful transmission occurs, provided that the transmission attempt is successful:

$$veh^*(\mathbf{P}) = \frac{\sum_{i=1}^{N} i \cdot \Pi_{V_i}(\mathbf{P})}{\Pi_T(\mathbf{P})}, \tag{11}$$

$$sl^*(\mathbf{P}) = \frac{\sum_{r=1}^{CW} r \cdot \Pi_{S_r}(\mathbf{P})}{\Pi_T(\mathbf{P})}. \tag{12}$$

Finally, we will compute a lower and upper bound on the delay incurred by the packet to reach the destination area in the described scenario. As a first step, we compute these bounds for one successful transmission, as it is done in [5]. Let us call $L(\mathbf{P})$ to this delay, and T_{packet} to the time duration (in slots) for a packet transmission. If there is a collision, then the delay is at least T_{packet}, so

$$L(\mathbf{P}) \geq (1 - \Pi_T(\mathbf{P})) \cdot T_{packet} = LB_1(\mathbf{P}). \tag{13}$$

On the other hand, if there is a successful transmission in one round of contention, its latency is $sl^*(\mathbf{P})$. If there is a collision, $L(\mathbf{P})$ is at most $CW + T_{packet} + L(\mathbf{P})$. Hence, $L(\mathbf{P}) < \Pi_T(\mathbf{P}) sl^*(\mathbf{P}) + (1 - \Pi_T(\mathbf{P}))\,(CW + T_{packet} + L(\mathbf{P}))$, and simplifying, we obtain the expression for the upper bound

$$UB_1(\mathbf{P}) = sl^*(\mathbf{P}) + \left(\frac{1}{\Pi_T(\mathbf{P})} - 1\right)(CW + T_{packet}). \tag{14}$$

Now, for the total average delay, the lower and upper bounds are computed as follows:

$$LB(\mathbf{P}) = LB_1(\mathbf{P}) \cdot hops(\mathbf{P}), \tag{15}$$

$$UB(\mathbf{P}) = UP_1(\mathbf{P}) \cdot hops(\mathbf{P}), \tag{16}$$

where $hops(\mathbf{P})$ is the average number of hops needed by the packet to reach the destination area when the matrix $\mathbf{P}$ is used for the slot selection. It depends on the distance of the average winner vehicle and the destination area to the source

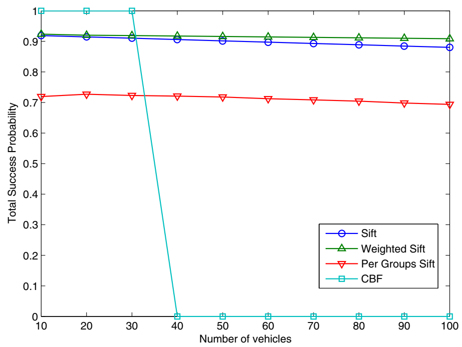


Fig. 1. Total probability of a successful transmission with respect to the number of contenders.

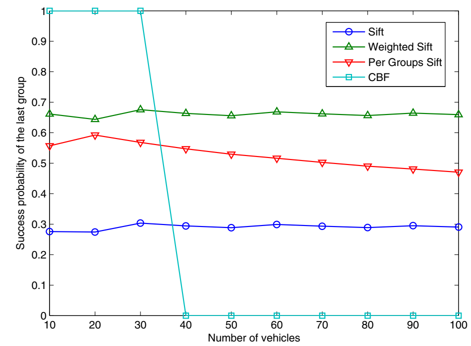


Fig. 2. Probability of a successful transmission for the last group of vehicles, with respect to the number of contenders.

node, denoted as $dist(veh^*(\mathbf{P}))$ and $dist(Dest)$, respectively. It is computed as follows:

$$hops(\mathbf{P}) = \frac{dist(Dest)}{dist(veh^*(\mathbf{P}))}. \tag{17}$$

B. Results

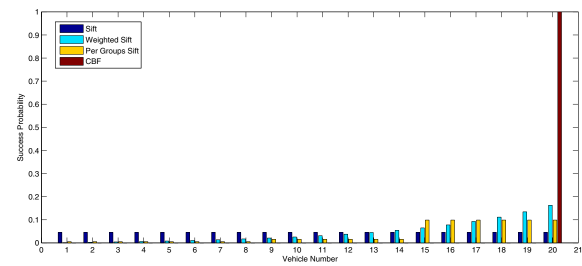
The total probability of a successful transmission and the probability of a successful transmission for the last group of vehicles are shown in Figures 1 and 2, respectively, for the two proposed protocols, as well as for the original Sift protocol and for a basic Contention Based Forwarding (CBF) algorithm. The number of vehicles is varied between 10 and 100, while the contention window is always fixed to 32 slots. For the *Per groups Sift* protocol, 3 groups are used and the corresponding contention windows are 8, 16 and 32 slots. For the basic CBF mechanism, we assume nodes select the slot r as the closest integer to $CW(1 - dist(V_i)/R)$ with probability 1, where $dist(V_i)$ is the distance from the node to the source.

It can be seen in Fig. 1 that when the number of vehicles is small (up to 30) the success probability for the CBF is 1, clearly outperforming the other protocols. However, when the number of vehicles increases, the success probability becomes 0, because more than one vehicle is always close enough to select the same slot. On the contrary, the other proposals scale much better, maintaining almost the same success probability. The same holds for the probability of a successful transmission for the last group of vehicles (Fig. 2).

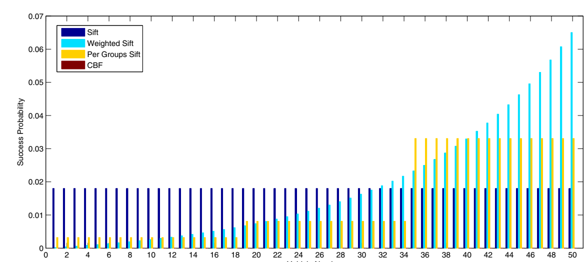
Let us recall that our main goal is to give higher priority to the farthest vehicle. Our proposals achieve this goal and outperforms other possibilities. Looking at Fig. 1 again, the total success probability for the *Weighted Sift* is slightly superior than Sift, whereas for the *Per groups Sift* it is significantly lower than the others. Nevertheless, when we observe the success probability of the last group of vehicles (Fig. 2), both the *Weighted Sift* and the *Per groups Sift* clearly outperform the original Sift protocol.

In Fig. 3 the probability of a successful transmission for each vehicle is shown when the number of contenders is fixed to 20 (Fig. 3(a)) and 50 (Fig. 3(b)).

As shown in Fig. 3(a), the probability of basic CBF is concentrated on the last vehicle, but when the number of vehicles is 50 (Fig. 3(b)) the success probability drops to zero for all the contending vehicles. For the two proposed protocols we can see better in Fig. 3(b) how the probability grows when approaching the last vehicle/group of vehicles.



(a) Scenario with 20 contenders.

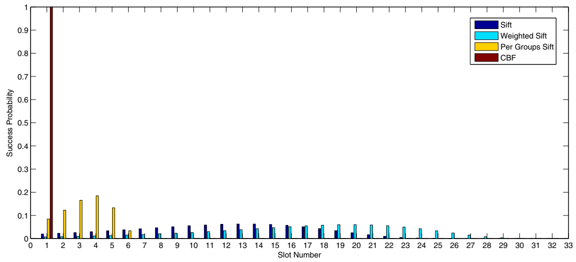


(b) Scenario with 50 contenders.

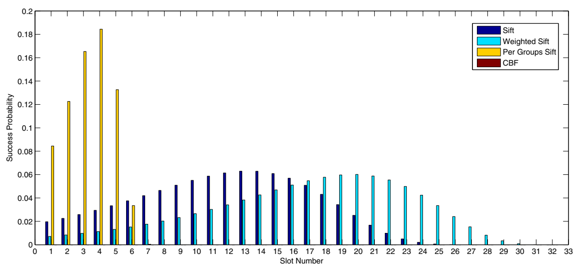
Fig. 3. Probability of a successful transmission for each vehicle.

In Fig. 4 the probability of a successful transmission in each slot is represented when the number of contenders is fixed to 20 (Fig. 4(a)) and 50 (Fig. 4(b)). For the first case, we can observe that the probability for the CBF is concentrated on the first slot, but when the number of vehicles is 50 (Fig. 4(b)) the success probability is zero for all the slots. Looking at Fig. 4(b) we can observe that the *Per groups Sift* gives a high success probability to the first few slots. On the other hand, the original Sift outperforms the *Weighted Sift* in terms of the slot success probability, since the latter gives more success probability to later slots, which increases the forwarding delay. It seems that Sift would perform slightly better in terms of delay. However, if we actually consider the average delay to the destination, that is, the multihop or end-to-end delay the results are different as discussed next.

We consider a multi-hop scenario, where the destination



(a) Scenario with 20 contenders.



(b) Scenario with 50 contenders.

Fig. 4. Probability of a successful transmission in each slot.

TABLE I
LOWER AND UPPER BOUNDS ON THE AVERAGE DELAY FOR ONE SUCCESSFUL TRANSMISSION.

Protocol	Lower Bound (slots)	Upper Bound (slots)
Sift	3.08	14.31
Weighted Sift	2.57	17.54
Per Groups Sift	8.63	26.09

area is situated at different distances (ranging between 400 and 800 m) from the source node, with $R = 300$ m. We assume the time duration of a packet transmission to be 30 slots, and the number of vehicles in the transmission range equal to 60. For each protocol, the lower and upper bounds on the average delay for one successful transmission, eq. (13) and (14), are shown in Table I, whereas the lower and upper bounds on the total average delay to reach the destination area are shown in Fig. 5. Thus, when we take into account the number of hops needed by the packet to reach the destination area, we can see how the *Weighted Sift* outperforms the usual Sift, unlike the *Per Groups Sift*.

V. CONCLUSIONS

In this paper we study CBF mechanisms for GeoNetworking implemented at MAC layer. We considered two schemes that use geometrically-distributed contention slots. We have analytically evaluated the total and per-vehicle success probabilities and the average delay bounds and compared them with a basic CBF mechanism and the original Sift protocol. Our results show that a weighted geometric distribution effectively prioritizes the access based on position for a wide range of vehicle densities, while retaining the benefits of geometrical distributions with respect to success probabilities and delay bounds. In particular, while a CBF mechanism with static timers needs to adapt the contention window size to the number of contenders to avoid packet collisions, the proposed

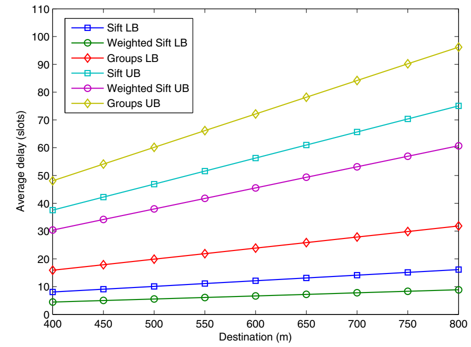


Fig. 5. Lower and upper bounds on the expected delay incurred by the packet to reach the destination area when it is situated at different distances (ranging between 400 and 800 m) from the source node and $R = 300$ m.

mechanisms scale gracefully and do not even need to know the number of contenders. With respect to the end-to-end delay, since the computed lower and upper bounds are weak, a realistic simulation is needed to show the true benefits of the proposed protocols, which is left as future work. On the other hand, we have arbitrarily fixed several parameters of the distribution, e.g., the window size. We leave as future work as well a more detailed study on how to choose the more appropriate parameters and their influence.

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