Abstract—A significant issue in vehicular ad hoc networks (VANETs) is the design of an effective broadcast scheme which can facilitate the fast and reliable dissemination of emergency warning messages (EWM) in the vicinity of an unexpected event, such as a traffic accident. In this work we propose a novel solution to this problem, which we refer to as Speed Adaptive Probabilistic Flooding (SAPF). The scheme employs probabilistic flooding to mitigate the effects of the broadcast storm problem, typical when using blind flooding, and its unique feature is that the rebroadcast probability is regulated adaptively based on the vehicle speed in order to account for varying traffic densities within the transportation network. The motivation behind this choice is the identification of the existence of phase transition phenomena in probabilistic flooding in VANETs which dictate a critical probability being affected by the varying vehicle traffic density, and shown to be linearly related to the vehicle speed (a locally measurable quantity). The scheme is evaluated using simulations on different sections of the freeway system in the City of Los Angeles. Simulation results indicate that the proposed scheme fulfills its design objectives, as it achieves high reachability and low latency of message delivery in a number of scenarios. The scheme is also shown to outperform existing solutions, including GPS-based, and exhibits robustness with respect to different road topologies and parameters such as the transmission range of vehicles and the number of hops.

I. INTRODUCTION

The 802.11p standard [1], which is part of the IEEE WAVE protocol stack, supports both vehicle-to-vehicle and vehicle-to-infrastructure communications allowing the formation of vehicular ad-hoc networks which are envisioned to accommodate the new generation of cooperative safety applications. Vehicular ad hoc networks can extend the information horizon to the drivers and cooperative hazard warning applications may utilize this spatially broader view of the surrounding environment to alert drivers of potentially dangerous situations.

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at an earlier stage. In case of an unexpected event such as a traffic accident, a weather hazard or a road works hazard, a vehicle appropriately equipped to detect the event will become an abnormal vehicle and utilize the underlying vehicular ad hoc network to issue emergency warning messages (EWMs) to all neighboring vehicles warning them of the imminent danger. A major challenge in such a scenario is the design of the information dissemination scheme which will facilitate the reliable and low-latency transfer of the emergency warning message to all vehicles in the vicinity of the unexpected event. It is critical that all vehicles within the area of interest receive the emergency warning message with high probability, since a single uniformed vehicle can cause a traffic accident, and it is also significant that the transfer is completed with the minimum possible delay in order to give additional time to the driver or the automated collision avoidance system to respond to the potential danger and improve the safety level on the road.

A straightforward solution to the aforementioned problem is blind flooding [2], a scheme which involves each vehicle rebroadcasting the emergency warning message whenever it receives it for the first time. However, the ability of blind flooding to fulfill the design objectives is challenged by stressed communication channel conditions in cases of high vehicular traffic densities. Blind flooding is known to work effectively in sparse and moderately dense networks, however its performance degrades significantly in highly dense networks where a large number of redundant messages are generated. These redundant messages lead to unnecessary message collisions, increased contention and high latency, which challenges the stringent delay requirements of the considered application. The problem is widely known as the broadcast storm problem [2] and a number of solutions have been proposed in literature to mitigate its effects [3]-[12]. The main idea has been to reduce the number of nodes rebroadcasting the message without affecting in a significant way the total number of nodes receiving the message. The various proposed solutions then differ in the method with which this restricted set of nodes is chosen, their overhead, and the reachability and latency they achieve.

Specifically for VANETs, the most popular approach has been to choose vehicles which lie on the boundary of the transmission range of the vehicle transmitting each message [13]-[15]. However, this method assumes the availability of a positioning system, such as GPS, which increases the signalling overhead, thus itself contributing to congestion. Furthermore
one cannot assure that a GPS signal is always available and that it is not influenced by external conditions such as the weather and tall buildings. Our main contribution in this work is to develop Speed Adaptive Probabilistic Flooding (SAPF), a new broadcast scheme which does not rely on the existence of a positioning system and is shown to work effectively in a number of scenarios outperforming blind flooding [16]. The scheme is intended to serve cooperative hazard warning applications in highway settings, however, it may be adapted to serve similar applications in city streets. The protocol employs probabilistic flooding [17] to mitigate the effects of the broadcast storm problem and has the unique feature of being able to adapt to changing traffic densities, ensuring high reachability and low latency of message delivery at all times, by regulating the rebroadcast probability based on the vehicle speed. Low vehicle speeds in a highway setting imply large vehicular densities in which case low rebroadcast probability values are sufficient to achieve the posed design objectives of high reachability and low latency of message delivery.

It is known that probabilistic flooding in mobile ad hoc networks is characterized by phase transition phenomena [18], similar to the ones observed in the context of random graphs and percolation theory [19], which suggest the existence of a critical rebroadcast probability value beyond which high reachability is achieved with high probability. For a particular traffic density there is thus a critical probability which gives the desired rebroadcast probability value. This value achieves the lowest latency of message delivery among all rebroadcast probability values whilst achieving high reachability. Speed Adaptive Probabilistic Flooding is able to calculate and adapt this critical probability at all traffic densities by means of a suitable rebroadcast probability function whose input variable is the vehicle speed. The existence of phase transition phenomena has been demonstrated using simulations but has also been verified analytically based on a simple model of equidistant vehicles on a straight line road.

The protocol enjoys a number of benefits relative to other approaches: it is simple to implement, it does not introduce additional communication burden as it relies on local information only (the vehicle speed); it does not require additional exchange of beacon messages for mutual awareness; it does not rely on the existence of a positioning system which increases the signalling overhead and may not always be available; and above all mitigates the effect of the broadcast storm problem, typical when utilizing blind flooding. The scheme is evaluated on different sections of the highway system in the City of Los Angeles using an integrated platform combining the OPNET Modeler [20] and the VISSIM simulator [21]. The reference road traffic models are generated on the VISSIM simulator and are used to generate mobility traces of the vehicles involved. These traces are then fed into the OPNET Modeler which is used to model the networking aspects of the proposed system. The simulation results indicate that the proposed scheme fulfills its design objectives as it achieves high reachability and low latency of message delivery with low signalling overhead in a number of scenarios reflecting different topologies and traffic conditions. The scheme is shown to be independent of the number of lanes of the freeway where it is applied, and it continues to perform as required when uni-directional traffic is replaced by bi-directional traffic. Moreover, the SAPF algorithm has been shown to outperform blind flooding in all scenarios and especially in cases of high vehicular density and the proposed solution, SAPF. We assume vehicles on a highway the rationale behind our design choices and the proposed algorithm, the Speed Adaptive Probabilistic Algorithm (SAPF), in section III we prove the existence of phase transition phenomena analytically, in section IV we present the simulation experiments conducted for design and evaluation purposes and in section V we offer our conclusions.

II. THE SPEED ADAPTIVE PROBABILISTIC FLOODING SCHEME

In this section, we describe the considered problem, we outline the rationale behind our design choices and we present the proposed solution, SAPF. We assume vehicles on a highway setting appropriately equipped to participate in vehicular ad hoc networks which utilize the 802.11p standard for multiple access. The normal traffic flow on the highway is at some point disrupted by an unexpected event such as a traffic accident, a lane change, a weather related hazard, etc. Upon detection of the unexpected event a vehicle becomes an abnormal vehicle and generates an emergency warning message which it desires to communicate to all vehicles in the vicinity of the unexpected event to warn them of the imminent danger. In this paper, we do not discuss details as to how this detection is achieved. We assume detection of the unexpected event which initiates the broadcast process and concentrate on the measures taken after this initiation. The primary objective of this work has been the design of a decentralized, simple to implement short range multi-hop broadcast scheme which ensures high reachability and low latency of message delivery with low signalling overhead. The broadcast storm problem poses the most significant challenge to the fulfillment of the above objectives in cases of high vehicular density and the proposed solution, which we refer to as Speed Adaptive Probabilistic Flooding, SAPF, solves the problem by employing probabilistic flooding. Upon receiving a message for the first time, a vehicle decides to rebroadcast the message with probability \( p \) and decides not to rebroadcast the message with probability \( 1 - p \).

A major challenge in the design of the SAPF protocol has been the derivation of the rebroadcast probability function
which maps the speed of the vehicle to the rebroadcast probability value in case of an emergency warning message being received for the first time. In a highway setting, the speed of the vehicle is sufficient to provide information regarding the vehicle density by means of speed density curves which can be readily obtained from field data [22]. This implies that the problem of deriving a function which maps the speed of the vehicle to the rebroadcast probability can be reduced to the problem of deriving a function which maps the density of the vehicles to the rebroadcast probability. The question that arises is then the following: for a particular vehicle density, what is the rebroadcast probability which achieves the highest possible reachability with the minimum possible latency. In this work, for each vehicle density we obtain such rebroadcast probability values by taking advantage of phase transition phenomena [23] observed when relating the reachability with the rebroadcast probability. For a particular vehicle density, there exists a critical rebroadcast probability beyond which all vehicles receive the message with high probability thus achieving high reachability. This critical probability is the desired rebroadcast probability value for the vehicle density under consideration. So, in order to derive the desired rebroadcast probability function we adopt the following methodology: we first choose a suitable set of vehicle density values; for each vehicle density we conduct simulation experiments which we use to obtain rebroadcast probability vs. reachability curves; on these curves we identify the critical probability value at the onset of the phase transition; we then use the obtained data to construct the probability vs. density curve and finally we combine the latter with the speed density curve to obtain the desired rebroadcast probability function. All the conducted simulation experiments which lead to the desired rebroadcast probability function are presented in section IV.

In the rest of this section we present implementation details of the proposed Speed Adaptive Probabilistic Flooding scheme. The protocol is implemented above the MAC layer. Each SAPF message has four designated fields in the packet header which store the following: the IP address of the originator, the destination address which is set to broadcast, the time to live (TTL) and the sequence number. All these fields are set by the originator of the message which is the Abnormal Vehicle at the time of the creation of the emergency warning message. The only field that can be modified in transit is the time to live field, TTL. The TTL field is decreased by one every time the EWM is rebroadcasted. As soon the TTL reaches a zero value the message is dropped. The TTL depicts the number of hops the EWM can be transmitted in the network. Each vehicle maintains a table of recently received messages. Each message is identified by a combination of the source IP address and the sequence number. Whenever a vehicle receives a new message, it checks whether this message has been recently received through matching of the identifiers in the relevant table. If no matching is found, the message is classified as being received for the first time, its identifier is added to the table of recently received messages and is made available for rebroadcast upon decision of the probabilistic flooding algorithm. Based on the obtained rebroadcast probability function, the SAPF algorithm works as follows:

**Speed Adaptive Probabilistic Flooding algorithm**

```plaintext
while node n receives EWM for a first time and it is not the originator of the EWM and TTL ≥ 0 do
    TTL = TTL - 1
    if veh. speed ≥ 15km/h and veh. speed ≤ 110km/h then
        broadcast EWM with probability
        p = 0.22*veh. speed + 2.4
    else
        if veh. speed < 15km/h then
            broadcast EWM with p = 0.05
        else
            if veh. speed > 110km/h then
                broadcast EWM with p = 1
            end if
        end if
    end if
end while
```

It must be noted that the rebroadcast probability versus speed function is derived based on the speed versus density curved obtained for the specific road under consideration. This implies that for each road different rebroadcast probability functions can be derived based on the speed versus speed density curve of the highway under consideration. These parameters are calculated either offline or online based on the real time measurements and communicated to the vehicles using static infrastructure. However, this increase in implementation complexity proved to be unnecessary, as later in the paper we show robustness of the derived algorithm with respect to changing highway topologies.

### III. Analysis

Our design is based on the observation that when applying probabilistic flooding, there exists a critical probability beyond which high reachability is achieved with high probability. It is thus important to verify the existence of such phase transition phenomena analytically. In this section we first utilize a simple mathematical model of a vehicular network on a single lane road to derive a difference equation which can be used to find numerical values of the probability of all vehicles receiving the critical message as a function of the retransmission probability. The solution of this difference equation is shown to exhibit phase transition phenomena similar to the ones observed using simulations. We then extend our analysis to a two lane road and we derive a lower bound on the probability of all vehicles receiving the message. It is worth noting that the analysis reveals the inherent existence of recursion in the analysis of probabilistic flooding schemes.

#### A. One Lane Analysis

We assume a straight line roadway section on which n equidistant vehicles move along a straight line. The vehicles have a common transmission range and the distance between
the vehicles is set to half the transmission range. The latter implies that when a vehicle transmits a critical message, four vehicles in the vicinity of the transmitter can receive the message, two in front and two at the back. The vehicles are indexed by integers \( \{1, 2, 3, \ldots, n\} \) in ascending order from left to right, with vehicle 1, denoted by \( v_1 \) being the left most vehicle. Without loss of generality we also assume that vehicle 1 is the initiator node which generates the critical message and broadcasts it for the first time. The rest of the vehicles employ probabilistic flooding in order to disseminate the message to all vehicles. So, a vehicle, upon receiving the critical message for the first time decides to rebroadcast the message with probability \( p \) and decides not to rebroadcast the message with probability \( 1 - p \). The above setting can be represented by a graph \( G(V, E) \) where \( V \) is the set of nodes and \( E \) is the set of edges. Each vehicle \( v_i \) is considered a node \( n_i \) in this representation and two nodes \( n_i, n_j \) are associated with an edge \( (i, j) \in E \) if the one lies in the transmission range of the other. Since the transmission range of the vehicles is equal to double the common distance between the vehicles, the graph can be defined as follows:

\[
G(V, E), \quad V = \{n_i, i \in [n]\} \quad (1)
\]

\[
E = \{(i, i + 1), (i, i + 2) \mid 1 \leq i \leq n - 2\} \quad (2)
\]

Assume now that in the above setting the initiator node broadcasts the initial message and that the rest of the nodes employ probabilistic flooding to disseminate the message to all nodes. We represent the nodes which have sent or received a critical message by a graph \( G_0 = (V_0, E_0) \) where \( V_0 \) is the set of nodes which have sent or received a critical message. An edge \( (i, j) \) lies in \( E_0 \) if node \( n_i \) has sent a message to \( n_j \) or if node \( n_i \) has received a message from \( n_j \). Note that \( V_0 \subseteq V, E_0 \subseteq E \). If the critical message has been received by all vehicles then \( V_0 = V \). The following transforms the reachability problem into a graph theoretic connectivity problem:

**Lemma 1:** \( V_0 \) is a connected graph

**Proof:** Assume in contradiction that \( G_0 \) consists of more than one non-empty connected disjoint components \( G_1, G_2, G_3, \ldots, G_i, i \leq n \). Denote by \( G_1 \) the component which contains the initiator node \( n_1 \). The initiator node \( n_1 \) lies in \( G_0 \) for sure since it is the one which initially broadcasts the message. Since \( G_j, j = \{2, 3, \ldots, i\} \) are disconnected from \( G_1 \), it means that no node from \( G_1 \) was able to transmit the unknown message to any node in \( G_j, j = \{2, 3, \ldots, i\} \). Since \( G_j, j = \{2, 3, \ldots, i\} \) can only receive the critical message from \( G_1 \), it implies that \( G_j, j = \{2, 3, \ldots, i\} \) is empty. Since we initially assumed \( G_j, j = \{2, 3, \ldots, i\} \) to be non-empty we have reached a contradiction.

Our objective is to compute the probability of all vehicles receiving the critical message. That is we aim at calculating the probability of \( V_0 = V \). We denote this event by \( U \) and we denote the probability of \( U \) occurring as \( \Pi(n) \), since \( |V| = n \). To compute \( \Pi(n) \) we consider the application of the probabilistic flooding algorithm on the considered topology as the experiment and we represent the probability space of this experiment using a probability tree diagram. The tree corresponding to \( n \) nodes is denoted by \( T(n) \). The tree diagram in the case of \( n = 5 \) is shown in Fig. 1. In this representation, each node \( B_i \) denotes the event that node \( i \) rebroadcasts the message assuming that it has received it, whereas \( NB_i \) denotes the event that node \( i \) does not rebroadcast the message. The probability that node \( i \) rebroadcasts the message is equal to \( p \) whereas the probability that node \( i \) does not rebroadcast the message is equal to \( 1 - p \). This dictates the branch preceding each node \( B_i \) and \( NB_i \). To each branch preceding node \( B_i \) we associate a probability \( p \) whereas to each branch preceding \( NB_i \) we associate a probability \( 1 - p \). Each of the possible outcomes at the \( n'th \) level of the tree is denoted by \( S \) and is indexed by \( k \in K \). Note that \( U = \bigcup_{k \in K} S_k \) is the event of all vehicles receiving the message which is the event of success.

![Fig. 1: Probability tree diagram for the case of five nodes.](image1)

In \( T(5) \) note that when two consecutive nodes \( i, i + 1, i \leq 3 \) do not broadcast then the algorithm terminates without success. On the other hand if node \( i \) broadcasts then the algorithm continues and we may consider node \( i \) as the initiator of the tree rooted on \( i \) denoted by \( T(n - i + 1) \). Finally, if node \( i \) did not broadcast, the only case that allows further propagation of the critical message, is node \( i + 1 \) to broadcast the message. In this case, we may consider node \( i + 1 \) an initiator of a tree rooted at \( i + 1 \). The latter tree is denoted by \( T(n - i) \). We can now redraw the tree diagram for the case of \( n \) nodes taking into account internal trees of similar structures. This leads to recursion. The tree is shown in Fig. 2.

![Fig. 2: Probability tree diagram indicating recursion.](image2)

The nodes \( B_3 \) at level 3 of the tree are the roots of trees \( T(n - 2) \). The node \( B_4 \) at level 4 of the tree is the root of tree \( T(n - 3) \). The set of successful outcomes generated by each of the trees are denoted by \( W_1, W_2 \) and \( W_3 \) respectively as
shown in the diagram. From the tree diagram one can derive the following difference equation.

\[
\Pi(n) = P(W_1) + P(W_2) + P(W_3) = pp\Pi(n-2) + p(1-p)p\Pi(n-3) + (1-p)p\Pi(n-2)
\]

\[
p^2\Pi(n-2) + p^2(1-p)\Pi(n-3) + (1-p)p\Pi(n-2)
\]

\[
p\Pi(n-2) + p^2(1-p)\Pi(n-3)
\]

The initial conditions of this difference equation are obviously \(\Pi(1) = \Pi(2) = \Pi(3) = 1\). The solution of this difference equation yields the probability of all vehicles receiving the critical message in the setting described above. The difference equation is not trivial to solve in closed form, so in order to gain insights on its behavior we solve it numerically and in Fig. 3 we plot \(\Pi(n)\) as a function of \(n\) for different values of \(n\).

We observe strictly increasing functions of \(p\). In addition, we observe areas where the probability of all vehicles receiving the message is low and areas where the probability is high. The transition from one area to the other becomes more and more abrupt as the number of nodes increases. The above analysis verifies the existence of phase transition phenomena associated with probabilistic flooding despite the simplicity of the considered model.

\[
\text{Fig. 3: Probability of all vehicles receiving the critical message versus the retransmission probability for different values of } n.
\]

**B. Two Lane Analysis**

We now assume 2n vehicles on a two lane straight line roadway section as shown in Fig 4. The vehicles are equidistant and have a common transmission range. The vehicles in the upper lane are indexed by integers \(\{1, 2, 3, \ldots, n\}\) in ascending order from left to right, with vehicle 1, denoted by 1U being the left most vehicle and vehicles in the lower lane are also indexed by integers \(\{1, 2, 3, \ldots, n\}\) in ascending order from left to right, with vehicle 1, denoted by 1D being the left most vehicle. The distance between the vehicles is set to half the transmission range. This implies that when a node \(iU\) (1D) broadcasts a message, the message can be received by nodes \(iU - 1, iU, iU + 1, iU + 2\) of the upper lane of the graph \((iD - 2, iD - 1, iD + 1, iD + 2)\) of the lower lane and by nodes \(iD - 1, iD, iD + 1\) of the lower lane of the graph \((iU - 1, iU, iU + 1)\). Without loss of generality we assume that vehicle 1U is the initiator node which generates the critical message and broadcasts it for the first time. The rest of the vehicles employ probabilistic flooding in order to disseminate the message to all vehicles. So, a vehicle, upon receiving the critical message for the first time decides to retransmit the message with probability \(p\) and decides not to retransmit the message with probability \(1-p\). Such a two lanes graph of \(n\) nodes on each lane is denoted by \(L_{2n}\). The \(L_{2n}\) graph together with the broadcast range of an illustrative number of vehicles is shown in Figure 4.

We wish to compute the probability of all nodes in the \(L_{2n}\) graph receiving the message. This is denoted by \(P(\text{Success } L_{2n})\). In general, we denote by \(P(X)\), the probability of event X to occur, where X is any event in the sample space of the probabilistic flooding experiment we are considering. We denote, for any node \(iU\) (1D, respectively) the event that \(iU\) receives and broadcasts the message, as \(iUB \) (1DB). In addition, the event that \(iU\) (1D) does not broadcast the message is denoted as \(iUNB\) (1DNB). For clarity of presentation in the subsequent discussion we assume that all the definitions that apply for vehicles in the upper lane also apply for the vehicles in the lower lane with the \(U\) notation replaced by \(D\).

**Lemma 2:** Assume application of the probabilistic algorithm on \(L_{2n}\). When nodes 2U, 3U, 1D and 2D do not broadcast the message after receiving it, the algorithm terminates and nodes 4U and 3D do not receive the message. The latter nodes are the first nodes that may not receive the message.

**Proof:** Nodes 2U, 3U, 1D and 2D receive the message due to the initial broadcast by the initiator. Nodes 4U and 3D may receive the message only from nodes 2U, 3U, 1D and 2D. If none of them broadcasts, the message will never be received by nodes 4U and 3D. Thus, the algorithm terminates.

So, by Lemma 2, in order for the algorithm to have positive probability to succeed on \(L_{2n}\), it must be that the algorithm does not terminate at nodes 4U and 3D. The complement of the event of both 4U and 3D not receiving the message consists of the following disjoint events.

- \(E_1 = 3UB&2DB\)
- \(E_2 = 3UB&2DNB\)
- \(E_3 = 3UNB&2DB\)
- \(E_4 = 3UNB&2DNB\) and the message is received by at least one of the nodes 4U, 3D from at least one of the nodes preceding nodes 3U, 2D, i.e. at least one of the nodes 1D, 2U broadcast it.

\[
\text{Fig. 4: The two lane graph } L_{2n}. \text{ The nodes receiving the critical message when the initiator node and an arbitrary intermediate node broadcast are illustrated.}
\]
The above events are disjoint since each of them contains the complement of a subset of any of the other events. Denote as \( P(\text{Success } L_{2n} \& E_i) \) the probability of all nodes in \( L_{2n} \) receiving the message when event \( E_i \) has occurred, \( i \in [4] \). Since the events \( E_i \) are disjoint it follows that

\[
P(\text{Success } L_{2n}) = \sum_{i=1}^{4} P(\text{Success } L_{2n} \& E_i)
\]

(4)

Before computing the probability of each of the events \( \{E_1, \ldots, E_4\} \) to happen, we consider a partition of \( E_4 \) which represents all the possible ways with which the event can occur. The partition is the following:

\[
E_4 = \bigcup_{i=1}^{3} E_{4/i}
\]

(5)

where events \( E_{4/i}, i = \{1, 2, 3\} \) are given by:

- \( (E_{4/1}) = 2\text{UB} \& 1\text{DNB} \& 3\text{UNB} \& 2\text{DNB} \)
- \( (E_{4/2}) = 2\text{UB} \& 1\text{DB} \& 3\text{UNB} \& 2\text{DNB} \)
- \( (E_{4/3}) = 2\text{UNB} \& 1\text{DB} \& 3\text{UNB} \& 3\text{DNB} \)

The reasoning behind this partition is that the nodes that precede nodes 3U and 2D are nodes 2U and 1D. So, in order to partition event \( E_4 \), one has to consider all possible actions of nodes 2U and 1D. Excluding the event of both nodes not broadcasting which is not allowed by the definition of \( E_4 \), the rest of the combinations are 2UB&1DNB, 2UB&1DB, 2UNB&1DB. When one combines the latter cases with 3UNB&2DNB which also stems from the definition of \( E_4 \) one obtains the above events. From equation (4) and the fact that \( E_{4/i} \) are a partition of \( E_4 \) it follows that:

\[
P(\text{Success } L_{2n}) = \sum_{i=1}^{3} P(\text{Success } L_{2n} \& E_i) + \sum_{i=1}^{3} P(\text{Success } L_{2n} \& E_{4/i})
\]

(6)

From the above equation one can thus identify six disjoint events which lead to the total probability of all vehicles receiving the critical message. Below, due to lack of space, we indicatively show the analysis for the success probability of two of these events. The rest of the cases are similar in nature and are presented in technical report [24].

1) Computation of Probability of Success on Event \( E_1 \): We first compute the probability of success of the algorithm when event \( E_1 \) occurs, i.e. we compute \( P(\text{Success } L_{2n} \& E_1) = P(\text{Success } L_{2n} \& (3\text{UB} \& 2\text{DNB})) \). Event \( E_1 \) is illustrated in Figure 5.

![Fig. 5: The event \( E_1 = 3\text{UB} \& 2\text{DB} \). Nodes 3U and 2D broadcast the message. Dotted arrows indicate receiving nodes due to 3U broadcasting whereas line dotted arrows indicate receiving nodes due to 2D broadcasting.](image1)

![Fig. 6: The event \( E_2 = 3\text{UB} \& 2\text{DNB} \). Node 3U broadcasts the message. Dotted arrows indicate receiving nodes due to 3U broadcasting.](image2)

Note that \( P(3\text{UB} \& 2\text{DNB}) = p \cdot p = p^2 \), since each of the nodes 2D and 3U receive the message from the initiator node and broadcast with probability \( p \), independent of each other. We observe that when 3U and 2D broadcast the message, they act as initiators of two lane graphs. When 3U broadcasts the message it acts as the initiator of a two lane graph consisting of \( 2(n-2) \) nodes whereas when 2D broadcasts the message it acts as the initiator of a two lane graph consisting of \( 2(n-1) \) nodes. The receiving nodes when 2D broadcasts is a subset of the receiving nodes when 3U broadcasts. We thus continue the analysis assuming that only 3U broadcasts. This assumption creates a lower bound on the calculated success probability but due to the preceding observation we expect this lower bound not to be conservative. It follows that:

\[
P(\text{Success } L_{2n} \& E_1) \geq p^2 \cdot P(\text{Success } L_{2(n-2)})
\]

(7)

2) Computation of Probability of Success on Event \( E_2 \): We now compute

\[
P(\text{Success } L_{2n} \& E_2) = P(\text{Success } L_{2n} \& (3\text{UB} \& 2\text{DNB})).
\]

Event \( E_2 \) is illustrated in Figure 6.

Note that \( P(3\text{UB} \& 2\text{DNB}) = p \cdot (1-p) \). Nodes 3U and 2D receive the message from the initiator node and the former broadcasts with probability \( p \) and the latter does not broadcast with probability \( 1-p \), independently of each other. We observe that node 3U acts as the initiator of a two line graph consisting of \( 2(n-2) \) nodes and it thus follows:

\[
P(\text{Success } L_{2n} \& E_2) = p \cdot (1-p) \cdot P(\text{Success } L_{2(n-2)})
\]

(8)

As indicated above, the success probability of the rest of the events can be found in [24]. Adding the success probabilities of all the events we get the following lower bound for the probability of all vehicles receiving the critical message. The proof can also be found in [24].

**Theorem 3:** The probability of success of the algorithm on a two line graph \( L_{2n} \) is lower bounded by

\[
P(\text{Success } L_{2n}) \geq p \cdot P(\text{Success } L_{2(n-2)}) + (p^2 + (p^2 + 3)(1-p)^3 + p^5 - 2p^1) \cdot P(\text{Success } L_{2(n-3)})
\]

(9)
In this section we present all the simulation experiments conducted in order to design the proposed speed adaptive probabilistic flooding scheme and evaluate its performance. All our simulation experiments are conducted using an integrated platform combining two simulators: the traffic simulator VISSIM and the OPNET Modeler. The time history of the positions of all vehicles, throughout a simulation experiment is first generated by Vissim and is stored in a single file. This file is then furnished into the OPNET simulator which simulates the networking aspects of the chosen scenario. Note that the OPNET Modeler does not model diffraction and reflection effects, multipath fading or the Doppler Effect. It merely uses a free space path loss model for radio wave propagation. The topology of the reference simulation model is a section of the I-110N freeway in the Los Angeles Area from the Slauson Exit until the Vernon Exit. This is a four lane freeway section spanning a distance of approximately 7km. In all experiments, we assumed an accident occurring on the considered topology 1km before the Vernon exit at the corresponding freeway entry, approximately 12 minutes after the start of the simulation. This provided sufficient time for the system to converge to its equilibrium state prior to the unexpected event. Just after the accident, we assumed a vehicle becoming an abnormal vehicle and employing 3-hop probabilistic flooding to communicate an emergency warning message to all vehicles in the vicinity of the unexpected event. The values extracted for each of the variables considered in this study were averages over 10 repetitions of the same simulation experiment. In order to create simulation models which generate realistic representations of the actual traffic conditions, the inflows in the chosen test site are set according to field measurements obtained through the PEMS system. Three sets of data were considered reflecting three different traffic conditions: light, medium and heavy. The classification was based on the location of the corresponding points on the speed density curve of the considered freeway section, shown in Fig. 9(b). The SAPF scheme was implemented on the OPNET Modeler by making appropriate modifications to the 802.11a WLAN station model which excludes implementations of layers above the MAC. In this model the transmission power was set to 0.0039w to ensure a transmission range of 300m. The vehicles are configured to operate in broadcast mode with no ACK/CTS/RTS mechanisms. The time to live field is set to 2 in order to guarantee a maximum 3-hop transmission. This creates a multi-hop transmission range of approximately 1000m. The packet size is set to a constant value of 1024 bytes. In all simulation experiments, the accident is assumed to occur 700 seconds after the simulation start time, approximately 1km before the Vernon exit. All simulations run for 1000 seconds simulated time, and it is repeated 10 times to obtain statistical averages. Our objective has been to investigate the performance and the robustness of the proposed scheme with respect to the chosen performance metrics. Two basic performance metrics were considered: the achieved reachability and the latency of message delivery. The achieved reachability is defined as the percentage of downstream vehicles within the multi-hop transmission range of the vehicle generating the emergency warning message which eventually receive the message, while the latency of message delivery is defined as the time interval between the instant that the message is generated and the instant that the message is received for the last time by some vehicle.

A. Protocol Design

In section II we have analyzed the rationale behind the design approach and have indicated that the most important part of the design procedure is the extraction of the critical probability function. The first step towards finding the critical probability function is to choose a set of vehicle density values. For each vehicle density, a critical probability is to be found beyond which high reachability is achieved with the fewest number of messages exchanged. The values chosen were 2.5, 5, 7.5, 10, 12.5, 15, 20, 25, 30, 35, 40, 50, 60, 70 measured in vehicles per kilometer per lane, which represents a light to heavily loaded freeway. In the simulation experiments that we conducted, the vehicle density was set by appropriately setting the vehicle penetration rate in the test site under consideration. For each vehicle density value, a reachability vs. rebroadcast probability graph was obtained. Rebroadcast probabilities in the range 0 to 1 in steps of 0.05 were considered. Fig. 7 shows the reachability values obtained as we varied the rebroadcast probability for a subset of the vehicle density values under consideration. For each vehicular density, the reachability exhibits a strictly increasing and concave behavior as the rebroadcast probability increases and eventually converges to values close to 100%. There thus exists a critical threshold probability beyond which almost all vehicles receive the emergency warning message with high probability. This behavior is compatible with phase transition phenomena observed in the literature of random graphs and percolation theory [18]. In this work we define the critical probability as the rebroadcast probability which achieves a reachability value equal to 95% of the value to which it eventually converges. For each vehicular density this critical probability is the desired rebroadcast probability. The reason for this is that among all rebroadcast probability values which achieve almost 100% reachability this is the one which minimizes the latency, the
number of rebroadcasts and the contention. This is a result of these quantities relating to the rebroadcast probability through strictly increasing functions. This behavior is verified in Fig. 8 for the topology under consideration. The figure shows plots of the number of backoffs and the latency of message delivery as we increase the rebroadcast probability. Both quantities exhibit the expected monotonically increasing behavior. A vehicle enters a backoff state in the event of a message collision and the number of backoffs is thus a measure of the observed contention.

Fig. 8: As we increase the rebroadcast probability, both the contention and the latency of message delivery increase.

Having obtained the desired rebroadcast probability values for each of the considered vehicle densities, their relationship is depicted graphically in Fig. 9(a). We observe an exponential-like, monotonically decreasing behavior of the critical probability as the vehicle density increases. This is expected, as higher vehicular densities suggest that smaller rebroadcast probability values are sufficient to ensure high reachability and low latency of message delivery which are the design objectives. The final step is to combine the obtained rebroadcast probability vs. density function used in the proposed SAPF scheme is shown in Fig. 10(a). We observe an almost linear relationship which is approximated with a linear function whose parameters are obtained through least squares fitting and is also shown in Fig. 10(a). The function is given by the equation:

\[ p = 0.22 \times v + 2.4 \]  

(10)

where \( p \) denotes the rebroadcast probability and \( v \) denotes the vehicle speed. The linear relationship obtained is used to determine the rebroadcast probability for vehicle speeds in the range 15km/h up to 110km/h. For speeds above 110km/h (speed limit) we set the rebroadcast probability equal to 1. The reason is that beyond such speeds it is impossible to estimate the density based on speed information only and so we adopt a rather aggressive rebroadcast policy in order to ensure message delivery to all vehicles. On the other hand for speed values below 15km/h, we assume that the network has almost reached its capacity and so we consider a constant rebroadcast probability of 0.05. The resulting rebroadcast probability vs. speed function used in the proposed SAPF scheme is shown in Fig. 10(b).

B. Comparison with Blind Flooding

In the rest of this section we evaluate the performance of the proposed speed adaptive probabilistic scheme using simulations. Our results indicate that the proposed scheme fulfils the posed design objectives as it achieves high reachability and low latency of message delivery, it outperforms blind flooding, it is location independent and robust to changing the number of hops and transmission ranges. We firstly evaluate its performance in the reference scenario, described at the beginning of the section and compare it with the performance of blind flooding when the freeway section under consideration experiences light, medium and heavy congestion. In Fig. 11(a)
we show the reachability values recorded by the SAPF and blind flooding schemes for each of the considered levels of congestion. In Fig. 11(b) we show the corresponding latency values. It is evident that SAPF manages to maintain high reachability values, comparable to the ones recorded by blind flooding and at the same time achieve significant reductions in the observed latency. As the transportation network becomes more congested, the negative effects of the broadcast storm problem cause blind flooding to require more time to deliver the emergency warning message to all vehicles in the area of interest. Speed Adaptive Probabilistic Flooding, on the other hand, manages to counterbalance the effects of the broadcast storm problem maintaining almost constant latency values, even as congestion increases. It thus manages to almost decouple the protocol behavior from the level of congestion on the highway and outperform blind flooding, especially in cases of heavy congestion, by achieving large reductions in the observed latency. The ability of the SAPF scheme to counterbalance the negative effects of the broadcast storm problem is also demonstrated in Figures 12(a) and 12(b) which show the number of rebroadcasts and the number of backoffs respectively reported by the two protocols as congestion increases. Increasing levels of congestion cause the vehicular network to become more dense which in turn causes blind flooding to rebroadcast a larger number of messages. These messages lead to increased number of collisions each of which causes nodes to enter a backoff state. So increased contention is reflected in the increased number of backoffs which are shown in Fig. 12(b). The SAPF scheme employs probabilistic flooding to reduce the number of relays thus achieving significant reductions in the number of exchanged messages. Its ability to adapt to changing traffic conditions is reflected in the number of rebroadcasts remaining almost constant as congestion increases. So the Speed Adaptive Probabilistic Flooding is successful in mitigating the effects of the broadcast storm problem by relieving the vehicular network from unnecessary rebroadcasts which consume useful bandwidth and ensuring almost constant levels of contention independent of the traffic conditions.

C. Effect of Highway Topology

The design parameters of the proposed SAPF scheme were tuned using field data from a specific section of the highway system. This raises concerns regarding the ability of the protocol to maintain good performance as the topology changes when the parameter values are kept constant. For each section, one may choose to ensure good performance by adopting the same design procedure off-line to specify the desired design parameter values of the protocol and then communicate these values to all vehicles entering the section either through the vehicular ad hoc network or via fixed infrastructure on the roadside. However, this significantly increases the implementation complexity and so our approach has been to keep the parameter values constant to the ones suggested in section III and investigate the robustness of the protocol with respect to changing highway topologies using simulations. Towards this end we have evaluated the performance of the proposed protocol at two other sections of the freeway network in the Los Angeles area. These sections were chosen to have different number of lanes in order to also investigate the effect of the number of lanes on the performance of the proposed scheme. The first one is a three lane section of the SR-60E freeway spanning a distance of approximately 4.5km and the second is a five lane section of the I-105E freeway spanning a distance of approximately 3km. As in the case of the I-110N test site, the inflows were obtained from field data available through the PEMS system and three sets of measurements were chosen to reflect light, medium, and heavy traffic conditions. In Fig. 13(a) we show the reachability achieved by blind flooding and the proposed SAPF scheme in all three considered test sites as congestion increases. In Fig. 13(b) we show the corresponding latency values. It is evident, that in all cases, the SAPF scheme achieves high reachability values comparable to the ones achieved by blind flooding and at the same time manages to achieve significant reductions in the observed latency. It is really striking to note that the SAPF scheme achieves almost constant latency values, independent of the specific highway topology and thus the number of lanes and also independent of the level of congestion on the highway. This demonstrates the robustness of the protocol and for the given design parameters, their independence from different topologies and lane numbers, and thus ability to bring major improvements to the achieved performance independent of the location where it is applied.
Despite the fact that the 802.11p standard has a maximum transmission range of 1000m, vehicles may choose to vary their transmission range during their operation. Power control in vehicular ad-hoc networks is a major issue, as varying transmission range values may bring significant improvements in the achieved end-to-end performance due to the dynamic nature of the vehicular density. It is thus important to ensure that the SAPF scheme continues to perform well as the transmission range changes. We again consider the reference scenario under heavy congestion and we compare the performance of blind flooding and the SAPF scheme for transmission range values in the range 200m to 1000m in steps of 100. Fig. 15 shows the recorded reachability and latency values. We observe that in all cases the SAPF scheme outperforms blind flooding as it achieves high reachability values and significantly reduces the observed latency.

**D. Effect of the number of hops and the transmission range**

The number of hops that emergency warning messages travel before they are dropped is a design parameter of the protocol, whose value can be changed based on the transmission range of the vehicles engaged in the vehicular ad-hoc network and the desired area within which all vehicles should receive the emergency warning message. It is thus important for the SAPF scheme to continue to perform well as the value of this parameter changes. In this section we investigate the ability of the SAPF scheme to achieve the latter using simulations. We consider the reference scenario on the I-110N freeway section and we set the inflows to values which cause the considered freeway to become heavily congested. The number of hops was changed by making appropriate modifications to the time to live field in the packet header. Values in the range 1 to 5 were considered. Fig. 14(a) compares the reachability values recorded by blind flooding and the SAPF scheme as the number of hops increases. Fig. 14(b) shows the corresponding latency values. We observe that as the number of hops increases both blind flooding and the SAPF scheme record high reachability values close to 100%. However, the SAPF scheme outperforms blind flooding as it consistently achieves smaller latency of message delivery values. Note also that as the number of hops increases the latency of both the SAPF scheme and blind flooding increase which is expected, as the message traverses a larger distance over a larger number of nodes.

Despite the fact that the 802.11p standard has a maximum transmission range of 1000m, vehicles may choose to vary their transmission range during their operation. Power control in vehicular ad-hoc networks is a major issue, as varying transmission range values may bring significant improvements in the achieved end-to-end performance due to the dynamic nature of the vehicular density. It is thus important to ensure that the SAPF scheme continues to perform well as the transmission range changes. We again consider the reference scenario under heavy congestion and we compare the performance of blind flooding and the SAPF scheme for transmission range values in the range 200m to 1000m in steps of 100. Fig. 15 shows the recorded reachability and latency values. We observe that in all cases the SAPF scheme outperforms blind flooding as it achieves high reachability values and significantly reduces the observed latency.

**E. Effect of a Bi-Directional Freeway topology**

The design of the SAPF algorithm was based on the assumption of one way traffic. One might question how SAPF performs if the opposite traffic was also taken into consideration. Earlier we have shown that SAPF has not been significantly affected by the number of lanes. It is interesting to investigate whether vehicles moving in the opposite direction have any (positive or negative) effect on the performance of the SAPF algorithm. One might expect that the vehicle speed will not always be representative of the density of the vehicles, since there will be additional vehicles in the opposite direction. It is anticipated that the worse results will be obtained when the opposite stream is congested. We have evaluated the performance of the SAPF algorithm using bidirectional traffic on the I110SN freeway in Los Angeles. The reference model and the simulation parameters are exactly the same as in section IV. As in the case of the I110N test site, the inflows were obtained from field data available through the PEMS system. The only difference in this scenario is that we have taken measurements in both driving directions at certain times and dates. To avoid the ambiguity between the implementation of the SAPF algorithm on the one way traffic scenario and the implementation of the SAPF algorithm on the bidirectional traffic scenario we name the former SAPF:1W and the latter SAPF:2W. SAPF:1W represents the
SAPF algorithm applied on the one way direction on the I110N freeway (North direction), and SAPF:2W represents the SAPF algorithm applied when considering traffic on both directions of the I110SN freeway, (South and North directions).

In Fig. 16 we show the reachability and the latency values achieved by the SAPF and BF algorithms in the considered topology. It is evident from the presented graphs that SAPF:1W and SAPF:2W perform very well under all traffic conditions, achieving high reachability and maintaining low latency. SAPF:2W performs better than BF:2W algorithm in all traffic conditions, by achieving higher reachability values and lower latency values in the range of 7ms to 11ms in contrast to 15ms to 21ms achieved by the BF:2W algorithm. The question that arises is whether the performance of SAPF:2W is comparable to that of SAPF:1W. Before any assessment is made, we investigate the characteristics of the two traffic streams. We focus on the "medium" traffic scenario and the investigation is made with reference to the vehicle speeds and densities that exist in both directions. On the I110N freeway section considered for the one way traffic scenario, 423 vehicles are accommodated with vehicle speeds in the range of 41-98km/h, as opposed to the freeway traffic on the I110S freeway section for the same period of time, where 276 vehicles are accommodated with vehicle speeds in the range 100-108km/h. Therefore, SAPF while operating in the freeway direction where the accident takes place, rebroadcasts with low probabilities since vehicle speeds are in the range of 41 to 98km/h, while on the opposite traffic direction SAPF broadcasts with higher probabilities since vehicle speeds are in the range of the 100 to 108km/h. This non-uniformity of the vehicle density and the high probability of message retransmission on the opposite direction causes, as shown in Fig. 16 and 17, the SAPF:2W to rebroadcast more messages than the SAPF:1W algorithm leading to a larger number of backoffs and thus higher latency values. This degradation of performance is not sufficient to cause the SAPF algorithm not to outperform the Blind flooding algorithm. Considering the above results it can be concluded that the SAPF algorithm performs reasonably well, even when both directions are considered, however its performance can be improved if one informs vehicles in the opposite direction not to rebroadcast. This can be achieved by employing a GPS system which identifies the direction of the abnormal vehicle and includes this information in the EWM. As the EWM is received by all approaching vehicles, in both directions, they have the potential to compare their direction with that in the EWM and if the two match they will use SAPF to disseminate the EWM, otherwise the message will not be rebroadcasted.

**F. Effect of the Speed Limit of the freeways**

The SAPF algorithm was designed for a specific road topology, the I110N a four lane freeway, with a speed limit of 105km/h. The question that may arise is how does SAPF perform on freeway sections with different speed limits. One might argue that since we rebroadcast with probability 1 when the speed is above 110 km/h the algorithm might exhibit slight degradation in performance, when the speed limit exceeds this value. To investigate the effect of speed limits, we consider the application of the SAPF algorithm in the following three freeway sections with different speed limits: the I105E a three lane freeway with a speed limit of 90km/h, the I110N a four lane freeway with a speed limit of 105km/h, and the I15N a four lane freeway with a speed limit of 112km/h.

The reference models, the simulation parameters and the performance metrics that were used for the above three road topologies are the same as in section IV. Fig. 18 shows the reachability and latency values, recorded by the SAPF algorithm for the three freeways and the considered levels of congestion. It is evident that SAPF manages to maintain high reachability values over 90% regardless of the different speed limits of each freeway, and also maintains good latency: 6ms at worst case.
G. Comparison with the ideal GPS protocol

As pointed out in the introduction, the most popular and effective approach to mitigate the effects of the broadcast storm problem in vehicular ad hoc networks and design a protocol which can facilitate the fast and reliable transfer of emergency warning messages to the vicinity of an unexpected event has been to choose vehicles on the boundary of the transmission range to rebroadcast the emergency warning message. However, this approach relies on the existence of a positioning system such as GPS which is associated with high signalling overhead, and may not always be available. So, in this work we propose an alternative which does not rely on the existence of such a system. It thus reduces the implementation complexity, however with an expected cost of somewhat increased limitations on the achievable performance. The availability of a positioning system enlarges the allowable design space and we consider the solution emanating from such an approach as the "optimal" one which pushes the system towards its performance limits. In this section we investigate the degree to which the proposed SAPF scheme deviates from such an idealized "optimal" solution. We consider the reference scenario on the I-110N freeway section in light, medium and heavy traffic conditions and we compare the performance of blind flooding and the proposed SAPF scheme with that of an idealized "optimal" protocol which utilizes a GPS system but without the necessary exchange of beacon messages to ensure that only one vehicle on the boundary of the transmission range of each vehicle retransmits the emergency warning message. Furthermore, we assume the availability of the GPS signal, with zero positioning error at all times. We refer to the latter idealized protocol as the GPSzo protocol. Fig. 19(a) shows the reachability values achieved by the three protocols as congestion increases. Fig. 19(b) shows the corresponding latency values. It is evident that all three protocols achieve high reachability values. In addition, we observe that despite the fact that blind flooding reports increasing latency values as congestion increases, both the SAPF scheme and the idealized GPS supported protocol manage to maintain almost constant values. As expected, the idealized GPS supported protocol reports smaller latency values than SAPF, with the difference being approximately 3ms which is more than satisfactory for the application under consideration. This demonstrates that the SAPF scheme significantly reduces the implementation complexity, at the cost of acceptable reductions in the achieved performance relative to the idealized "optimal" solution thus making it attractive for deployment in real situations.

H. SAPF vs. GPS with signaling overhead included, GPSwo

In the previous section, we have shown that the SAPF algorithm performs almost equally well as the idealized GPSzo protocol by achieving high reachability values and maintaining acceptable latency values in the order of a few milliseconds. However, the idealized GPSzo protocol was implemented (in the OPNET Modeler) without the necessary signalling overhead. In this section, we compare the SAPF algorithm with the GPSwo protocol that has been fully implemented to include all the necessary signalling information and evaluate its performance with respect to the resulting overhead. Again, it is assumed that the positioning device is 100% accurate and that the GPS signal is available at all times.

The GPSwo protocol works as follows: in the case of an unexpected event the AV (abnormal vehicle) broadcasts the emergency warning message to its neighbors and select a vehicle that lies at the outermost of its transmission boundary to be the rebroadcasting vehicle of the EWM. This process is repeated each time a vehicle receives a message and the TTL value of the message is higher than 0. This requires that all vehicles in the network are aware of the location of their neighbors. The location of each vehicle is most commonly obtained locally within each vehicle, using a GPS device. So, in order to locate the furthestmost vehicle in its transmission range, each vehicle exchanges small hello (beacon) messages periodically with other vehicles which include its identity (MAC address or IP address) and its location. A vehicle receiving a hello packet extracts the identity and location from the packet and computes the distance between the creator of the hello packet and itself. Furthermore, it updates its neighborhood table recording the vehicle’s MAC ID, the distance, and the time the hello packet was received. It is evident that the frequency of the message exchange (hello interval time) is an important design parameter as it influences the accuracy (and staleness) of the location of the vehicle.

In this model the transmission power was set to 0.0039W to ensure a transmission range close to 300m. The vehicles are configured to operate in broadcast mode with no ACK/CTS/RTS mechanisms. The time to live field is set to 2 in order to guarantee a maximum 3-hop transmission. This creates a multi-hop transmission range of approximately 1000 meters. The packet size is set to a constant value of 1024 bytes. In all simulation experiments, the accident is assumed to occur 700 seconds after the simulation start time. All simulations run for 1000 seconds simulated time. Our objective has been to investigate the performance and the robustness of the proposed scheme with respect to the chosen performance metrics.

We consider the reference scenario on the I110N freeway...
in light, medium and heavy traffic conditions and we compare the performance of the SAPF algorithm with that of the GPSwo algorithm. All experiments were repeated 10 times with different seed numbers. The presented values are averages over these ten repetitions. The 80% confidence intervals are also obtained. In Fig. 20 we show the obtained reachability and latency values vs. the hello interval time in the heavy traffic condition scenario. The hello interval time determines the period of hello packet exchange and attains values in the range 0.3s to 5s. Increasing the rate of hello messages exchanged, leads to improved accuracy of vehicle position estimation at the expense, however, of larger signalling overhead which can lead to larger latency. On average, each vehicle in this scenario moves approximately 15 meters per second. So, we choose to set the hello time interval in the range 0.3s to 5s, in order to ensure updates in the range of 5 to 75 meters at most. These values are adequate for our simulation purposes since in heavy traffic conditions a freeway section of length 75m contains sufficiently large number of vehicles. The same values have been considered for the medium and light traffic conditions, since the vehicles in these scenarios have higher velocities but are less densely spaced compared to the heavy traffic scenario.

Fig. 20: SAPF performs equally well as the GPSwo algorithm in low hello intervals, and even better in heavy traffic conditions with hello intervals greater than 1s. With respect to the latency achieved, SAPF is only 1ms slower which can be considered negligible.

It is evident from Fig. 20(a) that for hello time intervals equal to 1s and 2s, the SAPF algorithm achieves almost the same reachability values as the GPSwo algorithm. However, for values greater than 3s, SAPF outperforms the GPSwo algorithm, reaching 100% reachability. The GPSwo algorithm suffers a degradation in performance due to the stale positions of the vehicles at these time intervals. We discuss this in more detail later in this section. Fig. 20(b) shows the latency achieved by both algorithms. We observe SAPF to be 1ms slower than the GPSwo algorithm. This can be considered negligible, bearing in mind the overhead associated with the GPSwo algorithm. In Fig. 20, we can also see the confidence intervals of the SAPF and GPS algorithms. We observe that the SAPF algorithm exhibit smaller deviation of the reachability values. When considering the latency values, deviation is larger but still remaining within acceptable limits. Overall, the SAPF performance can be considered better than GPSwo.

Fig. 21(a) shows the number of backoffs reported in the network by both algorithms. It can be observed that the GPSwo algorithm reports a large signalling overhead under all traffic conditions (as expected). With hello interval times in the range 0.3s to 2s it generates many collisions and backoffs. It is obvious that SAPF outperforms the GPSwo algorithm considerably, recording number of backoffs values very close to 300 as opposed to GPSwo values in the range 1100 to 120000. It is worth noting that there is an exponential increase of the protocol overhead, as we decrease the hello interval time. In Fig. 21(b) we show the number of hello messages exchanged within the network for a duration of 12 seconds which is of the order of 1000. This can be contrasted with the number of messages created by the SAPF algorithm which is only 12. This demonstrates that the signalling needs of SAPF are much less than the GPSwo algorithm.

Fig. 21: SAPF outperforms the GPS algorithm by achieving low protocol overhead in heavy traffic conditions.

For the medium and light traffic conditions we only show the reachability and latency graphs since the results are similar to the ones we have discussed in the heavy traffic condition case. Fig. 22 shows the reachability and latency values recorded in the case of medium traffic. Both algorithms achieve high reachability values over 95% and very low latency. In the light traffic condition case, it is clear that GPSwo performs better than the SAPF algorithm, as far as the reachability and the latency are concerned. However, SAPF still maintains high reachability values in the range of 95% and above, and achieves latency values only 1ms slower than GPS algorithm, see Fig 23. These slight degradation in performance of the SAPF algorithm is acceptable bearing...
In this paper we propose Speed Adaptive Probabilistic Flooding, a novel short range multi-hop scheme which can facilitate the fast and reliable transfer of emergency warning messages to all vehicles in the vicinity of an unexpected event such as a traffic accident. Extensive simulations indicate that the proposed scheme fulfills its design objectives as it achieves high reachability and low latency of message delivery in a number of scenarios. Its robustness with respect to changing topologies, number of hops and transmission ranges is also demonstrated. The scheme is also shown to outperform existing solutions, such as Blind Flooding, and GPS-based.

V. CONCLUSIONS

In this paper we investigate the effect of highway curvatures on the performance of the SAPF algorithm. We consider a curved section of the I10E freeway in Los Angeles area from S. Central Ave exit until the S. Alameda St. In this setting and using simulation parameters identical to the ones used in previous experiments, we evaluate the performance of the SAPF algorithm compared to the GPSwo and Blind Flooding algorithms. The reachability and latency achieved by the three protocols are shown in Fig. 25. We observe similar behavior to what has been reported in previous experiments. High reachability values are observed and at the same time the GPSwo and SAPF algorithm manage to significantly decrease the latency values reported by the Blind Flooding algorithm. These results demonstrate that the curvature on the highway does not significantly affect the performance of the three protocols.

Fig. 23: In light traffic conditions, SAPF maintains high reachability values close to 95% and low latency values.

Fig. 24: Varying the hello garbage collector interval, the GPS algorithm can attain higher reachability values. In heavy traffic conditions, however, the SAPF algorithm still achieves higher reachability values, despite the considerably less signalling overhead.

I. SAPF vs. GPSwo in a curved highway section

In this section, we investigate the effect of highway curvatures on the performance of the SAPF algorithm. We consider a curved section of the I10E freeway in Los Angeles area from S. Central Ave exit until the S. Alameda St. In this

REFERENCES


