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Message forwarding based on vehicle trajectory history in Fully Distributed Traffic Information Systems

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ABSTRACT

Fully Distributed Traffic Information Systems (FDTIS) are based on vehicle-to-vehicle wireless data transmission that enables traffic self-organization. For instance, alert messages transmitted by vehicles in poor traffic conditions allow receivers to avoid congested roads and reduce travel time.

Such systems are of great practical interest and may provide excellent results in urban conditions due to the presence of numerous potential partners for most vehicles. Unfortunately, many applications already use the wireless transmission medium in cities, leading to frequent problems with saturation. In order to avoid such issues, FDTIS must generate as few transmissions as possible, while remaining effective. In the specific context of congestion avoidance, we present a method that improves the efficiency of traffic alert messages by directing them to the geographic regions where they are most useful. This method uses past trajectory data from the vehicles involved in a traffic jam, thus decreasing the number of messages. We compared the performance of our method in simulation to a reference implementation and showed that, in the case of intensive traffic, this method prevents saturation of the wireless medium which would have resulted in a general degradation in performance. From a macroscopic point of view, we also showed that the improvement in medium usage obtained had no impact on the ability of our system to ease traffic jams.

Keywords:

Distributed traffic information system Geocasting

Inter-vehicle communications Traffic simulator

Mobile ad-hoc network simulator

1. Introduction

In many countries, the development of urban, suburban or inter-urban transportation generates many traffic jams due to structural reasons or unexpected events. One possible means of combating traffic jams is to use a Personal Navigation Assistant (PNA). To allow users to reorganize their journeys, these PNA must be able to perform dynamic routing based on up-to-date data provided by a Traffic Information System (TIS). Such systems have already been proposed. The first were academic projects, e.g., Notice [1], SaveTime [2], Street Smart [3], TraffCon [4], SOTIS [5], Cartel [6], but several commercial or pseudo-free products are now available, e.g., [7,8] or [9].

Whatever the approach, vehicles require up-to-date traffic data. Thus, it is necessary to measure the current state of the traffic (*measurement*), construct a synthetic picture of this state (*aggrega-*

tion), and send this information to vehicles wishing to dynamically calculate their route (*diffusion*). Each of these three functions can be either *centralized* (i.e., performed by common equipment) or *distributed* (i.e., performed by the vehicles). In this article, we focus on systems where all the above functions are distributed, leading to the definition of Fully Distributed Traffic Information Systems (FDTIS).

FDTIS present important benefits, but also disadvantages. In dense urban environments in particular, they can contribute to the saturation of the communication medium. Literature-proposed approaches that fight against saturation operate at different levels. They are based on an analysis of the communication channels state (medium level), the geometric relationships between the partners that communicate (geometric level) or the various specificities of the application requiring communication (application level). Of course, several approaches can be used simultaneously in some proposals. At the medium level, [10] have proposed ATB, an adaptive protocol in which the partners continuously observe the medium occupation in order to optimize their own transmissions. At the geometric level, [11] have proposed the UMB protocol for selecting a transmitter located near a line segment. [12] have proposed a broadcast suppression

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technique based on the distances between partners that use the same highway. In the same paper, the flow direction is also taken into account because it is important information regarding the application. Finally, [13] have presented a similar but more general solution that also uses the neighboring relationships between partners. At the applicative level, [14] have proposed an adaptive transmission method based on an evaluation of the knowledge of traffic conditions that is held by the partners in the vicinity of the emitter.

In this article, we address specifically the problem of medium saturation at the applicative level by using the information provided by vehicles stuck in traffic. For this purpose, we developed an original method that takes into account the history of vehicles to route the traffic warnings to the regions where they are the most useful.

The rest of the paper is organized as follows: the next section provides a short review of Distributed Traffic Information Systems and presents typical issues relating to wireless data transmission in this context. In Section 3, we present the cooperation model we developed to implement and evaluate the system we propose. In Section 4, we present the data routing methods already proposed for data transmission; each is analyzed in order to verify if it can be used in the context of $FDTIS$. In Section 5, we present the principles of the protocol proposed in this paper to route the traffic data, as well as potential implementation issues. Finally, Section 6 provides an evaluation of the performances of our routing protocol in comparison with a reference protocol.

2. Review of traffic information systems

The first Traffic Information Systems (TIS) were based entirely on Traffic Information Centers (TIC). In these systems, traffic data were collected by sensors attached to the road network. (Notice [1], TMC [15], $TraffCon$ [4].) This information was sent to a traffic center where it was compiled and then transmitted to the end users by FM radio (RDS protocol). However, this architecture is poorly reactive and is not scalable because of instrumentation costs.

The low cost of geolocation technology (GPS) and the massive development of cellular phone networks has modified the structure of TIS because the vehicles themselves can now provide the instrumentation functionality,² in other words, these structures have become distributed. However, this kind of TIS is not fully distributed because it is still based on a TIC to which end-users must be connected by a cellular phone. The main interest of this architecture is to offer a global view of traffic conditions. Its other features can be seen as advantages or disadvantages, depending on your point of view. Here is a list of known disadvantages, from an end-user point of view:

- Users have to pay for both communications and traffic information services; so ironically, they have to pay for information they collect themselves.
- The toll-free systems currently available (e.g., Waze [9]) do not offer any confidentiality, they do not support any anonymization and allow the service provider broad access to the user's private life.
- The cellular phone network was not designed for continuous, massive usage, so an overload is likely to occur.
- The response time of these systems is not excellent due to delays related to the functioning of the Traffic Information Center.

This is why it makes sense to investigate distributed data transmission solutions (i.e., users can collaborate without any central mediator). For example, [16,5,3,14] and many others have studied such systems.

² The traffic jams detection can be done automatically or with the help of the drivers (TomTom HD Traffic [8], Coyote [7], Waze [9], Save Time [2]).

The advantages of Fully Distributed Traffic Information Systems ($FDTIS$) are the following: they are highly scalable, with no exploitation costs, and they can be very reactive when partners are physically close together. This reactivity allows traffic perturbations that have an immediate impact for users to be taken into account, as it allows them to change their trajectory very quickly. This feature is especially useful in urban contexts, where centralized traffic information systems are not fast enough.

These systems could be implemented because several low-cost wireless technologies are available (e.g., 802.11n or 802.11p) and administrations such as the National Highways Traffic Safety Administration ($NHTSA$) or the Department of Transportation (DOT) in the USA are currently promoting mandatory built-in vehicle-to-vehicle ($V2V$) communication technology for car safety [17].

However, $FDTIS$ use a medium that does not allow global communication. This is why one must use a data routing method in order to transmit information from partner to partner. Paradoxically, this need can lead to very different constraints, depending on the situation. Indeed, when the traffic is light, the main problem will concern connectivity between vehicles. Thomin et al. [18], for example, studied this situation. Conversely, when the traffic is denser, an informational storm is likely to occur and lead to the saturation of the medium [19] because the phenomenon is exponential. Informational storms occur in regions densely populated with partners, such as urban areas. This problem may be aggravated when other types of applications also use the medium, which is especially the case if the transmission uses a popular wireless technology, such as Wi-Fi (normalized as $IEEE$ 802.11). This is a particularly unproductive situation, as it penalizes all the users of the medium, including mission-critical safety applications.

The goal of this paper is to propose a way of minimizing the usage of the wireless medium in the context of $FDTIS$, even when the traffic is particularly dense.

3. The FORESEE framework

In $FDTIS$, the way in which the vehicles cooperate may have a huge influence on the traffic. This is why the project $FORESEE$ aims to build an efficient cooperation model that is tested in various situations using simulations. The first results of this project can be found in [14]. This paper presents the model itself and analyzes its behavior in standard, favorable situations. In [18], we analyzed its performance in a situation of informational famine related to the initial deployment of the system. The current paper addresses the inverse situation: how to avoid an informational storm provoked by a large number of cooperating partners.

In order to make the rest of the paper more understandable, this section presents an overview of the $FORESEE$ model. The simulator that implements this model is described in Section 6.2.

3.1. The FORESEE cooperation model

The $FORESEE$ model is based on a fully distributed system composed of a set of agents that are physically installed in each vehicle. Each agent is part of a driving assistant that evaluates the surrounding traffic conditions from data sent by the other agents via a wireless medium. This approach is typically cooperative because each agent only uses the information received from other agents. The model is logically supported by three sub-systems, as shown in Fig. 1:

- *Measurement*: this sub-system builds a quality indicator by comparing the vehicle's current speed with the speed deemed normal for the edge of the road network corresponding to the vehicle's current position. It produces a flow of scalar traffic quality indicators (Q_s), which provide an instantaneous

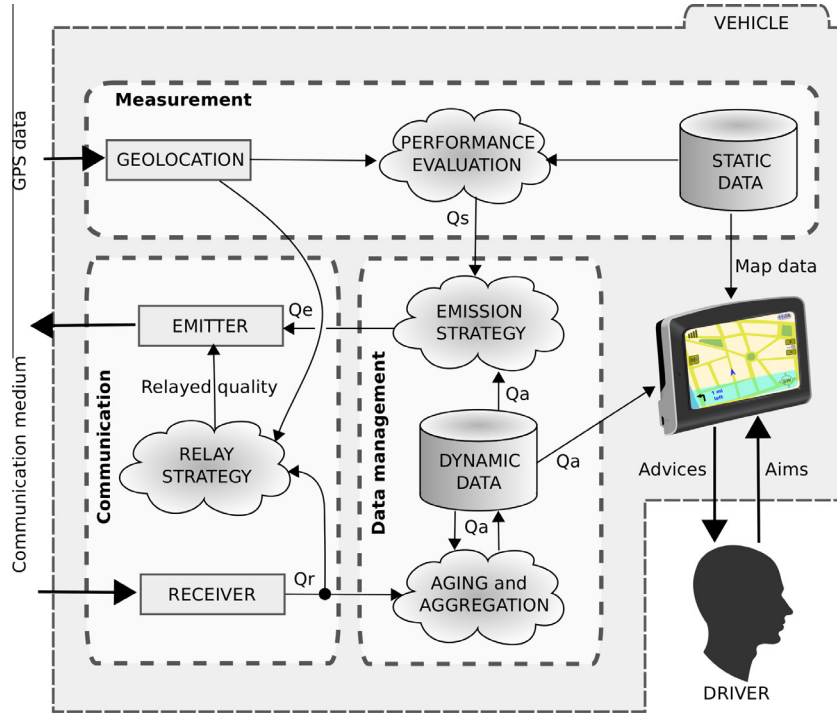


Fig. 1. Structure of a FORESEE agent.

evaluation of the traffic quality on each road segment used by the vehicle.

- *Data management*: this sub-system constructs a dynamic local view of the traffic by aggregation of the previous local view and data received from other vehicles. This data defines the *ambient quality* of the traffic (Q_a) for the current vehicle. As it is a local view of the traffic for the agent, this quality is central to our model. Our guesstimate is that the ambient quality provides a piece of information that is neither complete nor accurate, but that is sufficient to improve agent performance. A decision-making unit builds the quality data Q_e to be transmitted to the other vehicles. The elements of Q_e are built from the vehicle's self-knowledge quality Q_s , and the ambient quality Q_a based on arbitrary constraints related to the type of application.
- *Communication*: this sub-system communicates with the surrounding vehicles, and receives from them a flow of traffic quality indicators Q_r . The communication sub-system is also responsible for relaying, or not, the information received to other vehicles. This function allows the propagation of information beyond the communication range of direct communications.

3.2. Instantiation of the FORESEE model

This generic model could be used to build rather different systems by changing a whole sub-system or just its parameters. The communication sub-system is the basis of the protocol we propose in this paper; it will be described later. However, for the sake of comprehensiveness, the current section presents an overview of the instantiation of the other sub-systems.

3.2.1. Measurement

This sub-system computes a flow of quality indicators $q_s(t) = \frac{v(t)}{V_{k(t)}}$, where $v(t)$ is the speed of the vehicle at time t , $k(t)$ the road network edge where it is at this time and $V_{k(t)}$ the maximum legal speed limit on this edge. This indicator generally ranges

from 0 to 1, but is greater than 1 when the driver does not conform to the speed limit.

3.2.2. Data management

This sub-system comprises three parts:

1. The *aggregation* of quality indicators aims to build a local view of the road traffic, by performing a weighted sum of previous quality indicators and freshly received ones. The weight coefficients depend on the age of the data because the recent information is considered more reliable. Note that the reception of concordant information from the same edge of the road network reinforces the weight of this information.
2. *Data aging* is a mechanism that allows us to implement a traffic information system based uniquely on *incident reports* (or alerts). With this mechanism, the messages transmitted concern only bad traffic conditions, and no cancellation message is emitted when the traffic returns to a normal state. In our system, the decision to suppress the cancellation messages is justified by the poor quality of transmissions that makes it impossible to guarantee the correct reception of these messages. Indeed, the leakage of one of these messages would be catastrophic, as it would corrupt every local traffic view of partners having received the corresponding alert. The principle that has been chosen supposes that the quality of the traffic on an edge is good, with a probability that is proportional to the age of the last incident report received concerning this edge. This mechanism, inspired by the evaporation in stigmergic approaches, is implemented by an iterative computation of traffic quality on each edge:

$$q_a(t + \tau_s) = 1 - e^{-\frac{\tau_s}{\tau_r}}(1 - q_a(t)) \quad (1)$$

where τ_s is the sampling step of the system, τ_r a relaxation time and $q_a(t)$ the estimated traffic quality on this edge at time t .

3. The *emission strategy* helps decide when an alert must be transmitted. The two strategies currently available are a periodic transmission and an adaptive transmission that allows the number of alerts to be reduced [14].

With this instantiation, the system we describe here is purely reactive because the data management sub-system works by aggregating the data from partners, with no predictive algorithm. This design is not mandatory, but offers an efficient trade-off in our context because it keeps the implementation simple. Indeed, predictive approaches are less interesting in our FDTIS than in standard TIS because of the very short transmission delay.³ Moreover, predictions are useless when traffic jams are caused by an accidental event.

4. Data transmission in VANET for FDTIS

Ad-hoc networks are communication networks that do not have a fixed structure, and VANET (Vehicular Ad-hoc NETWORK) are ad hoc networks with in-vehicle nodes. Fundamentally, a FDTIS is based on a VANET. Indeed, VANET exhibit specific problems because the movement of vehicles makes it impossible for partners to establish stable connections. For this reason, transmission protocols are sometimes supported at application level instead of being performed by low-level network components. These protocols can be divided into two families: the first one is topology-based and uses routing tables; the second one is position-based and uses geographic information [20].

Whatever the routing type, some applications are not very demanding with regard to delivery time, or a delivery time cannot be guaranteed. In this case, protocols that favor a high delivery rate instead of a quick delivery can be used. An excellent survey about Vehicular Delay Tolerant Networks (VDTN) is provided in [21]. Although delay-tolerant protocols could be used in FDTIS, they should be avoided whenever possible because the data transmitted represents rapidly outdated traffic conditions. Moreover, fast delivery of traffic alerts allows users to change their trajectory soon enough, even when they are close to the point of contention.

The next subsections describe different ways of routing data in VANET, and evaluate how they fit the domain of FDTIS.

4.1. Table-driven routing

This kind of protocol is based on routing tables. These tables can only be built when the topology of the transmission network is known. Nodes are constantly moving, so the network's topology must be continuously updated (proactive approach). This is generally achieved by a continuous exchange of beacons between potential partners, generating considerable data traffic.

A variation of this protocol is to compute routes on demand, i.e., when a message has to be transmitted (reactive approach). Route discovery is generally achieved by flooding a request, and the best transmission node is selected on the basis of an arbitrary criterion, such as the shortest path. This kind of routing can be viewed as a lazy version of the previous one. Discovering a route considerably delays message transmissions, so this kind of routing is inappropriate when the frequency of messages is high. Moreover, as already mentioned for the previous protocol, optimal route discovery may generate high occupancy of the transmission medium. Whatever the routing method used, maintaining routing tables tends to consume a significant bandwidth, thus table-driven routing is not an option to minimize the usage of the medium when scattering many short messages.

³ In regions with good connectivity (e.g., urban regions), the transmission time is less than a few seconds.

4.2. Epidemic routing

Epidemic routing collectively designates flooding-based protocols. In the basic version of this protocol, nodes send copies of packets to every reachable node of the network. It is simple, and generally fast, but consumes a large wireless bandwidth and a lot of buffer space, which is why various improved versions of this protocol exist that try to limit the number of copies of packets. For example, [22] proposed a two-phase protocol that *sprays* a controlled number of copies over the network, then directly transmits the copies to the final destination. Similarly, [23] presented a single-copy propagation model that exploits the delay-tolerance of certain systems in order to optimize the resource consumption at the expense of delivery time. However, single-copy protocols are subject to poor delivery rates, thus the number of copies during epidemic routings is a trade-off between performance and resource consumption [24].

4.3. Opportunistic routing

Opportunistic routing protocols take advantage of the spatial nature of the wireless medium to dynamically select the best way to route data from an emitter to a receiver, when a contact is available [25]. For that purpose, a forwarder is selected among a set of candidates, but ultimately, several forwarders may be used. First proposed by [26], this kind of protocol selects the forwarder based on an arbitrary criterion, such as the shortest path [27], or the path that minimizes energy consumption [28]. Two families of opportunistic routing exist. In the first one, the emitter selects the set of preferred forwarders before sending a packet [29], at the expense of exchanging coordination messages. This feature may lead to high resource consumption [30]. In the second opportunistic routing family, the forwarder is selected after the packet has been sent. For example, [27] use a probabilistic selection based on the relative positions of emitters, forwarders and receivers. The advantage of this type of routing is that it can be implemented with less coordination effort as it relies on information that is known locally. Opportunistic routing implements the store-carry-forward paradigm, and consequently, it is typically used in delay-tolerant applications. For this reason, it provides a limited assurance that data will be delivered within a bounded time. This is why its usage in FDTIS is not a preferred option, but could be considered when the connectivity between partners is poor.

4.4. Geographic routing

Geographic routing is based on the position of the communication nodes, and the topological relationship between them is not taken into consideration [31]. With this kind of routing, first proposed by Navas and Imielinski [32], the recipient of a message is identified only by its position. For this reason, geographic routing is not based on a communication network in the traditional sense. Numerous protocols are based on geographical position: Lee et al. [20] proposed an analysis that classified them in a number of directions.

- *Delay-tolerant routing*: some protocols, such as VADD [33] or GeOpps [34], ensure message delivery although they do not guarantee a delivery time. On the contrary, non-delay-tolerant routing protocols, such as CBF [35], CAR [36] or GPSR [37], tend to deliver the messages quickly, but some of them may be lost.
- *Beacon routing*: partners may use beacons in order to know each other [13]. This knowledge is generally desirable, but the use of beacons is bandwidth consuming, which is why some protocols, such as BLR [38] or no-beacon GEDIR [39], aim to suppress, or to minimize, the use of beacons.

- *Auxiliary network-based routing*: certain algorithms take advantage of the structuring offered by the road network in order to select the nodes used to route the messages. This is the case of GPCR [40] or CAR [36] for example.

Geocasting is a variation of geographic routing in which the target of the messages is a set of nodes contained in an arbitrary geographic region. This kind of routing is especially interesting in applications that need to transmit data for collective use, which is the case of DTIS. With these applications, users do not need to subscribe to a service to gain access to the information provided; they can access the information by simply entering a certain geographic zone.

An interesting kind of geocasting uses the notion of forwarding zone. This zone is a region through which messages pass before reaching the target zone. The interest of this zone is to reduce the search area for a transmission partner, and to minimize the use of the medium. Moreover, the forwarding zones can match zones with a large number of potential partners, which contributes to routing data without loss. The choice of a proper forwarding zone allows efficient functioning, for a given application.

In the LBM (Location Based Multicast) protocol proposed by [41], the forwarding zone is the smallest rectangle surrounding the emitter and the target region. Stojmenovic et al. [42] proposed partitioning the potential forwarding zone with a Voronoi diagram based on partner position, then using the portion of the diagram that intersects the target region as a forwarding zone. The GeoGRID protocol [43] partitions the space as a 2-D grid. A node is then elected for each mesh, and is in charge of message forwarding.

Several authors have studied the effect of the shape of a forwarding zone. The underlying idea is that this shape must fit the type of target application. For example, Jochle et al. [44] studied performances with circular, rectangular or polygonal forwarding zones for three very different applications (local danger warning, emergency vehicle warning and ride-sharing request). Buchenscheit et al. [45] conducted a similar study for an emergency vehicle warning system. In order to minimize the risk of an accident involving an emergency vehicle, this system uses a forwarding zone that consists of a circular region associated with a polygonal region that contains part of the future trajectory of the emergency vehicle.

To the best of our knowledge, Niculescu and Nath [46] were the first to suggest guiding messages along a trajectory. In this paper, the concept of trajectory was taken abstractly, for example, as a parametric curve; it is not related to any particular applicative context. Similarly, Costa et al. [47] propose a method based on potential fields to attract the messages towards a target zone. However, the way to determine the fields that fit the application is not addressed. Determining such a trajectory is a subject that is little discussed because it strongly depends on the target application. Therein, papers by Buchenscheit et al. [45], Labiod et al. [48], Jeong et al. [49] are exceptions.

4.5. Geocasting in FDTIS

FDTIS use VANET in a very particular way because traffic data has no identified recipient, either individually or collectively. For this reason, message transmission based on geocasting seems to fit this application, but the choice of the best target region remains an open issue. This is why many implementations proposed, such as [14] or [45], use a flooding-based message transmission method. This kind of diffusion guarantees that almost all the vehicles receive the messages, so many of them receive messages they do not need. In other words, the flooding-based transmission methods are *sensitive*, but not *accurate*.⁴

⁴ In our context, the terms *accuracy* and *sensitivity* will be defined in more detail in Section 6.

We postulate here that geocasting-based message diffusion might provide a better trade-off between accuracy and sensitivity. However, an approach like this implies knowing the geographic zones where the messages are likely to be most useful.

A protocol that is able to reach this goal is presented in the next section.

5. History-based message forwarding in FDTIS

The History-Based Forwarding (HBF) protocol is a geocasting protocol in which road traffic flows are used to infer both the target region and the forwarding zone of the messages. The underlying idea of this model is as follows: the road traffic is not randomly distributed, but composed of traffic flows of various intensities. One or several vehicle flows feed a traffic jam when it occurs, and contribute to the congestion in proportion to their scale. An efficient manner to reduce this congestion is thus to limit or to suppress the input flows by directing the alert messages along these flows. In this way, the drivers most concerned will be able to avoid the traffic jam by selecting one of the possible alternative trajectories. Unfortunately, it is very difficult to obtain in a distributed way an overall view of flows that feed a traffic jam. However, we can assume that each vehicle involved in the traffic jam holds a portion of this view, in the form of its own past trajectory. From this assumption, a simple way of directing alert messages to the proper geographic regions is thus to use a forwarding zone built on the past trajectory of the vehicle that first emits the message. This approach has two properties that are supposed to improve the accuracy of transmissions between partners, without notably degrading their sensitivity.

- The regions that contribute significantly to a traffic jam will receive most of the alert messages. Conversely, the regions that do not contribute will not receive any messages.
- The messages will be directed mainly to the regions where road traffic exists. This point minimizes the risk of message loss caused by poor connectivity between partners.

5.1. Implementation of history-based forwarding

The system we propose supposes that all the vehicles are equipped with a device offering computing capabilities, geolocation, and vehicle-to-vehicle communication. Section 3 presents a general model for such a system. This equipment is able to compute routes according to the state of the traffic and to memorize the past trajectory of the supporting vehicle. This trajectory is an ordered set of points $T = \{T_i\}$ that summarize the past route of the vehicle (T_0 being the oldest point). When a slow-down occurs, the equipment emits a warning message that contains a unique identifier M , the current location P , the quality of the traffic at this point Q_p , and finally the past trajectory T of the vehicle.

This message is then diffused using *restricted flooding*, which means that each vehicle that receives this message is responsible for forwarding it or not. When the message is forwarded, the position of the last emitter is stored in the message as a curvilinear abscissa along the trajectory. We defined $\{F_i\}$ as the set of vehicles that had received a message from F . Each potential forwarder F_i maps to a corresponding point H_i that is the orthogonal projection of the position of F_i along the trajectory. Finally, the maximal transmission range is R .

The diagram in Fig. 2 shows an example of a trajectory for a message originating from E , last forwarded by F , of which the target is T_0 . Some potential forwarding vehicles are along the trajectory, i.e., they are on the road that has been used by E , but others (F_1, F_2 and F_5) are only in the vicinity of this trajectory.

A receiver F_i does not forward a message M in the following situations:

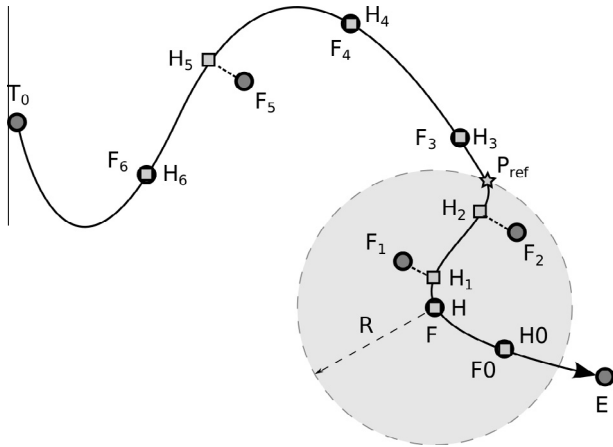


Fig. 2. Message trajectory and potential forwarders.

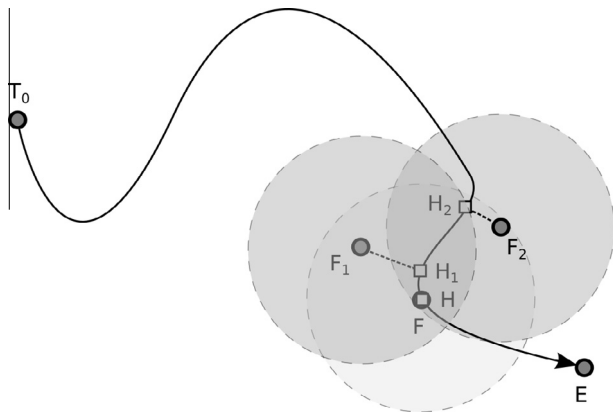


Fig. 3. Hidden terminal effect in the HBF protocol.

1. F_i has already received the message M .
2. The curvilinear abscissa of point H_i is greater than or equal to the curvilinear abscissa of the previous forwarding vehicle: $C(H_i) \geq C(H)$. This point guarantees that the message moves along the assigned trajectory toward T_0 .

In the example given, the potential candidates for forwarding are F_0, F_1 and F_2 , because they are within the communication range. However, F_0 will not forward the message because it does not satisfy condition 2. It is also possible that it does not fulfill condition 1.

This strategy does not exclude that multiple partners might forward a message. In our example, nodes F_1 and F_2 could both forward the message, but this is neither useful nor desirable regarding our objectives. On the contrary, it is desirable that only the partner in the best position forwards the message. However, proactively electing the best partner (i.e., through information exchange) is not possible because we have decided to use a protocol without beacons. This is why we have implemented a distributed election based on a timer, similar to the one proposed by [35] for the CBF protocol.

The principle of this election is as follows: each potential forwarding partner computes the difference between its own curvilinear position, and the position of a reference point P_{ref} along the trajectory known by all the potential partners. For example, this point might be T_0 , the final destination of the message. The greater the difference, the later the message is transmitted. In this way, the partner that is closest to the reference point is the first to forward the message. The other partners then drop the message

because of the above condition 1 (a copy of the message was received before the forwarding was triggered). In order to meet this condition, the difference of the emitting time of different vehicles should be greater than the time needed to transmit and process the message, as we discuss later.

Regarding the election of the best partner, the location of the reference point P_{ref} is of little importance. However, this choice is critical for the temporal performances of the system. Indeed, the function that computes the transmission delay will have the form:

$$\text{delay}(F_i) = k \times (C(P_{ref}) - C(H_i)) \quad (2)$$

However, it is not possible to find a value for the coefficient k that simultaneously distinguishes two close potential partners, and guarantees that the best one will transmit its data after a very short delay, ideally null. In fact, the first constraint implies that k must be very large, but the second one implies that it must be very small. A simple way to solve the problem is to choose a reference point known by all the partners and which is as close as possible to the best partner. For this purpose, we chose a point P_{ref} along the trajectory that is at a distance equal to the maximum communication range from the last forwarder, as shown in Fig. 2. In this way, a partner using the wireless communications optimally will transmit the message immediately. For the example presented in Fig. 2, the worst partner⁵ will transmit after an arbitrary delay of δt , but F_2 will transmit after a delay of $d_2 \times \delta t$, and F_1 after a delay of $d_1 \times \delta t$, with $0 \leq d_2 < d_1 \leq 1$.

The choice of the k parameter of Eq. (2) is of great importance because it must be high enough to avoid multiple forwarding of the same message. Let i and j be two potential forwarders, i being the best one. In order to ensure that j does not transmit a message that has already been transmitted by i , the difference in contention delays used by i and j must be greater than the time T used by the forwarders to transmit the message, augmented by various processing delays.

$$k \times (C(H_i) - C(H_j)) > T \quad (3)$$

Eq. (3) provides a simple way to determine an efficient value for k . For example, messages forwarded by two vehicles separated by a discrimination distance D_d do not overlap in time if $k > \frac{T}{D_d}$.

It is best to mention that the protocol proposed is subject to the *hidden terminal* effect. The diagram in Fig. 3 shows, for example, a situation that is similar to the previous one: F_1 and F_2 are again two potential forwarders, and F_2 is the best one. In this case, F_1 does not receive the message forwarded by F_2 and will wrongly forward the message. However, this problem is not likely to produce an information loss because this case would imply that the messages overlap in space and time. In other terms, two conditions must be met: (a) the receiver must be located in the region reached by both emitters and (b) the difference in distance from the emitters to the optimal forwarding point P_{ref} is less than the discrimination distance D_d mentioned above.

As these conditions have very little chance of being met simultaneously, the loss of messages due to the hidden terminal effect has very little influence on the system.

5.2. Implementation cost of the HBF protocol

Due to the need to transmit the trajectories, the extra implementation cost of the proposed protocol mainly concerns message length. It is especially desirable that the messages are encoded in only one packet, because using several packets adds a significant extra cost. Moreover, using a single packet for transmitting

⁵ The worst partner is a hypothetical partner that coincides with the last forwarder F .

messages has the advantage of avoiding any problems related to partial reception and simplifies the protocol. In order to quantify this issue, we supposed here that the wireless transmissions use the IEEE 802.11 standard (Wi-Fi). We also supposed that each location is represented by its GPS coordinates. Each position is thus represented by two real numbers, i.e., 16 bytes. Each message contains a 40-byte header (2×16 bytes for coordinates of the primary emitter and last forwarder, and 8 bytes for the unique message identifier).

As stated by the standard, a Wi-Fi data frame can handle a payload of up to 2312 bytes [50]; the remaining 2272 bytes leave space for encoding trajectories containing up to 142 points. An analysis of the digital map we used for our experiments shows that the average length of the edges is 68 m, which allows the transmission of trajectories of about 9600m in only one packet. This distance is amply sufficient to allow the vehicles to change their trajectories, and means that alert messages can be easily transmitted in only one frame.

Consequently, the extra cost specifically related to the transmission of trajectories will not exceed an upper bound corresponding to the maximum time needed to transmit a single Wi-Fi packet. This feature is of great importance because it allows a protocol to be built without any provisions for packet assembly, similar to the transport layer of the OSI model.

5.3. Scope of application of the HBF protocol

It is worth mentioning that the protocol presented here is intrinsically specific to the target application because it uses applicative data (the history of vehicles that are stuck in a traffic jam). This feature can be viewed as lacking generality, but it provides efficiency and keeps the implementation simple. Efficiency is a key quality here because the problem addressed is concrete and affects many people so the implementability of the solution proposed is important.

6. Experimental evaluation of the HBF protocol

6.1. Metrics

The various metrics presented in this section are based on the definition of several sets that allow the classification of vehicles according to their relationship with the messages. We first defined V as the set of vehicles on the road during the lifetime of a given message M . This set contains the two following subsets:

- V_c is the subset of vehicles concerned⁶ by message M . Symmetrically, one says that message M is useful for the elements of V_c .
- V_r is the subset of vehicles that have received message M .

This classification allows us to define four sets of vehicles in relation to message M :

- **True positives:** the set $V_c \cap V_r$ of vehicles that received a useful alert message.
- **True negatives:** the set $\overline{V_c} \cap \overline{V_r}$ of vehicles that did not receive a given useless alert message.
- **False negatives:** the set $V_c \cap \overline{V_r}$ of vehicles that did not receive a useful alert message.
- **False positives:** the set $\overline{V_c} \cap V_r$ of vehicles that received a useless alert message.

⁶ A vehicle is concerned by a message M if its future trajectory passes through or near the position of the primary emitter of the message.

The cardinality of these sets is of great importance to evaluate the protocol. For example, the higher the number of false positives, the greater the transmission medium load. Similarly, a high number of false negatives means that the system does not function properly. These remarks allow us to define below the well-known *accuracy* and *sensitivity* indicators for the HBF protocol.

6.1.1. Accuracy

The accuracy is an indicator of the capability of the system to direct messages *only* where they are useful. In other words, this indicator shows the capability of the system to use the transmission medium efficiently.

$$Accuracy = \frac{|V_c \cap V_r| + |\overline{V_c} \cap \overline{V_r}|}{|V|} \quad (4)$$

This indicator has a fixed upper boundary of 1 that is reached when only the vehicles concerned have received the message. Conversely, its lower boundary is 0, and is reached when the message has been received only by the vehicles not concerned.

One can remark that in the case of diffusion by massive flooding (high number of forwarding vehicles), almost all the vehicles receive the message, thus $V_r \rightarrow V$. In this case:

$$Accuracy \rightarrow \frac{|V_c \cap V| + |\overline{V_c} \cap \emptyset|}{|V|} = \frac{|V_c|}{|V|} \quad (5)$$

In particular, this shows that massive flooding works accurately when all vehicles are stuck in a single area, i.e., $V_c \rightarrow V$.

Another particular situation arises when the wireless medium is fully saturated. In this case, messages cannot be received so $V_r \rightarrow \emptyset$ and

$$Accuracy \rightarrow \frac{|V_c \cap \emptyset| + |\overline{V_c} \cap V|}{|V|} = \frac{|\overline{V_c}|}{|V|} \quad (6)$$

This equation shows that the accuracy tends towards the proportion of non-concerned vehicles when the wireless medium is saturated.

6.1.2. Sensitivity

The sensitivity (true positive rate) is an indicator of the capability of the system to direct the messages where they are useful. In other words, alerts are not transmitted properly when the sensitivity is low. This indicator is very important because a $FDTIS$ with poor sensitivity will fail to guide vehicles properly.

$$Sensitivity = \frac{|V_c \cap V_r|}{|V_c|} \quad (7)$$

The lower bound of the sensitivity is 0 (no message has reached a vehicle concerned), and its upper bound is 1 (all of the vehicles concerned by a message have received this message).

In the case of diffusion by massive flooding, $V_r \rightarrow V$, thus $Sensitivity \rightarrow 1$.

6.1.3. Total number of packets

The accuracy and sensitivity indicators measure the capacity of a protocol to guide messages to the regions where they are most useful. However, the total number of messages emitted and forwarded is also an important indicator of the stress imposed on the transmission medium by the protocol.

6.1.4. Vehicle performance

The main goal of a $DTIS$ is to improve vehicle performance for a given journey, thus it is important to know whether the transmission protocol used affects this performance. Several performance criteria can be taken into account: driver stress, fuel consumption,

overall distance, etc. Here, we chose to evaluate the temporal performance:

$$\text{Performance} = \frac{T_{\text{opt}}}{T_{\text{eff}}} \quad (8)$$

T_{opt} is the optimal travel time (related to the legal speed limit) and T_{eff} is the actual travel duration for a given vehicle.

6.2. The FORESEE simulator

6.2.1. Motivations and constraints

Real-situation experiments in relation to DTIS are expensive and very difficult to set up, so the use of simulations is a common option. However, the simulation of distributed systems dedicated to traffic improvement has to take into account two kinds of traffic simultaneously: *vehicle traffic*, and *wireless data traffic* between vehicles.

By *simultaneously*, we mean that the road traffic triggers wireless message transmissions between vehicles, which in turn contribute to modifying the initial traffic. This interplay obviously defines a closed loop system. To capture this characteristic, the simulator must ensure that each kind of simulated traffic can interact with the other one, leading to the definition of an *integrated simulator*. Moreover, we need to simulate a large number of vehicles to create traffic jams and an extensive road network to study wireless transmissions. The simulator should be able to support this complexity with an acceptable simulation duration. When the project started a few years ago, these two constraints led us to develop our own simulator⁷ because the simulators available at the time were composed of two separate decoupled or loosely coupled simulators [51].

6.2.2. Structure of the simulator

Our simulator is composed of three software components that continuously interact: the vehicle traffic simulator, the wireless data traffic simulator, and the application software. They are controlled via a GUI that allows the simulations to be configured and can display the road network and the vehicles during the simulation sessions. This GUI also provides access to several debugging services such as step by step execution, trace of message forwarding or breakpoint.

The first component is a micro-simulator for vehicle traffic. It includes a road network model, and a vehicle-following model derived from Treiber et al. [52]. The simulated time is discretized in a regular time slot of fixed duration T_s . At the beginning of each time step, the vehicle-following model is used to adjust the speed of the vehicles according to the surrounding traffic conditions, and the position of the vehicles is updated. T_s is tuned so as to assume that the position of the vehicles does not change significantly during the time slot relative to the radio range used in the wireless communications.⁸ In order to obtain good performances, the simulation engine has been deliberately kept simple, and the details that do not significantly influence the results have been ignored [53]. For example, we used simple priority rules because our objective was to study the traffic in terms of inter-vehicle communications, and not in terms of infrastructure.

The second component is a discrete-event wireless communications simulator, which runs in the simulated time slots in-between

the vehicle traffic simulation steps. It implements a simplified subset of the 802.11 standard for ad hoc wireless communications used in broadcast mode. Each vehicle manages a list of reachable neighbors, and inter-vehicle relationships are established at the beginning of each time slot using the model described in [14]. A function computes the probability of reception between two vehicles, and a geometric constraint restricts the propagation near the roadway. Among the various probabilistic models available, we used the Nakagami one because of its generic nature. During this procedure, the situation of the vehicles is checked, and an alert event is triggered if necessary. This will cause the chain of events related to the communication sub-operations described later.

Each vehicle also manages a local copy of the surrounding wireless medium. This copy is used to receive messages—it is populated with messages transmitted by neighbors—and to perform physical carrier sensing, needed to implement the basic DCF access procedure [50]. The transmission channel is assumed to be ideal:

- once a vehicle is reachable, no bit errors occur,
- the carrier sense range coincides with the communication range,
- the propagation delay is assumed to be the same for each reachable neighbor, regardless of its distance from the transmitter.

The wireless simulation follows the following steps:

1. A vehicle willing to broadcast an alert is allowed to transmit only if its medium is free, i.e., idle for a duration longer than a distributed inter-frame space (DIFS) period.
2. If the medium is busy, the backoff procedure is initiated. The vehicle waits for the medium to become free, then selects a random value from a range of integer values (the contention window, CW). This value is used to set a backoff counter, that is decremented at the end of each idle backoff slot period. The transmission is resumed when the counter reaches 0.
3. After a delay T_{switch} , that accounts for the physical layer receive-to-transmit switch time, the message is copied to the local medium of the neighboring vehicles. If it overlaps other messages (transmitted by vehicles outside the neighboring list of the transmitter, or started during the switch time), overlapping messages are tagged as dirty.
4. At the end of reception, an event is triggered for each receiver. The received message is filtered if it is dirty, otherwise, it is forwarded to the application software.

The third component is the application software that implements the vehicle cooperation model. It simulates the behavior of the device embedded in each vehicle. It implements the communication strategies (e.g. the relay strategy) and is responsible for maintaining the local view of the traffic in each vehicle.

6.3. Experimental conditions

The simulator presented in Section 6.2 was used for the simulations. These simulations were carried out on a road network in a small town,⁹ which is shown in Fig. 4. The corresponding digital map contains 1088 nodes and 2555 edges. A set of sources and sinks define the traffic flows, and a connection matrix provides the intensity of the flows connecting the sources and sinks. At the very beginning of its journey, each vehicle computes an optimal trajectory based on the legal speed limits on each edge of the network. During the journey, vehicles may periodically compute new trajectories based on the traffic alerts provided by the other vehicles. However,

⁷ The software is written in C++. It includes a GUI and a map editor allowing the road networks provided by the Open Street Map project to be imported. It contains about 38000 lines of code and uses the Qt graphic library.

⁸ For instance, a vehicle moving at 90 km/h travels 2.5 m during a T_s period of 0.1 s, this distance being 2 orders of magnitude less than a common outdoor wireless communication range.

⁹ City of Valenciennes, France (50.35711 N, 3.51833 E).



Fig. 4. Fragment of the digital map used for the numerical studies.

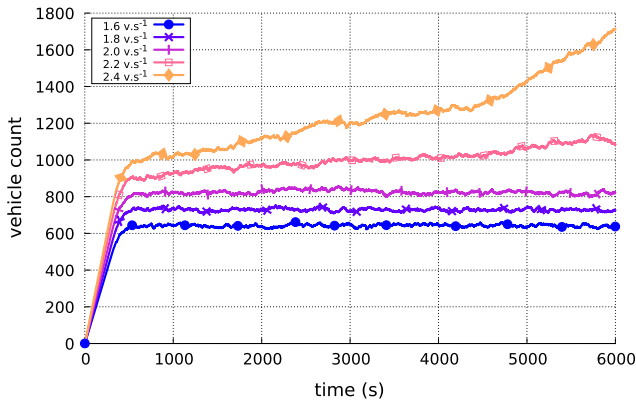


Fig. 5. Number of vehicles on the road as a function of time.

Table 1

Number of initial messages transmitted during the simulations as a function of traffic entry flow.

Entry flow (V/s)	Number of incident reports
1.6	848
1.8	1694
2	7903
2.2	60227
2.4	175,278

this possibility was disabled during the measurement of accuracy and sensitivity because the changes in trajectories would have made the comparisons between the tested protocols meaningless.

In this experiment, solely the vehicles use the medium, so no interaction with other radio traffic has to be taken into account. The radio transmission is configured with parameter values from the IEEE 802.11g specifications. The radio devices use only 1 channel, set to 54 Mbps, with an inter-frame space (IFS) of 50 μ s, a backoff contention window randomly chosen between 0 and 31 slots and a 20 μ s slot time. T_{switch} is set to 5 μ s. The Nakagami model used for computing the probability of reception is set to $m = 1$ with a 200 m propagation range, and an elliptic propagation

constraint with a 1/10 minor radius (20 m), accounting for the width of the streets [18]. A vehicle slowed by a traffic jam reports an incident immediately after detection, then every 10 s.

The duration of the simulations was set to 6000 s of simulated time,¹⁰ with the total number of vehicles varying from 9600 to 14,400, which gave us a number of vehicles on the road simultaneously varying from approximately 650 to 1700.

6.4. Protocol

The indicators presented above were evaluated in two situations:

- In the first study, we implemented the HBF protocol, as described in Section 5. We chose the k coefficient of Eq. (3) in order to provide a contention delay that fit the longest possible message. The maximum transmission time of this message was estimated to be about 530 μ s for a transmission speed of 54 Mbps (a payload containing 2312 bytes, a header of 30 bytes, a checksum of 4 bytes and a physical layer preamble of 188 μ s). Various processing delays must also be taken into account, so we used an actual transmission delay of 600 μ s. In order to discriminate two vehicles located at $D_d = 5$ m from each other, the k coefficient was set to $\frac{600}{5} = 120 \mu\text{s m}^{-1}$.
- The second study was based on the diffusion of alert messages using *improved flooding* (IF), as described in [18]. A receiver forwards a message only when it is farther from the original emitting point than the previous receiver, and discards duplicate messages. In order to fight informational storms, the probability of forwarding a message rapidly decreases as a function of the age of the message. Moreover, in this protocol we implemented the same contention mechanism as in the HBF protocol, except that we based it on the Euclidean distance¹¹ from the ideal

¹⁰ This simulated time corresponds to a real execution time ranging from 5 min to 6 h, depending on the intensity of wireless transmission activity.

¹¹ In the HBF protocol, the contention delay is based on a curvilinear abscissa along the forwarding trajectory.

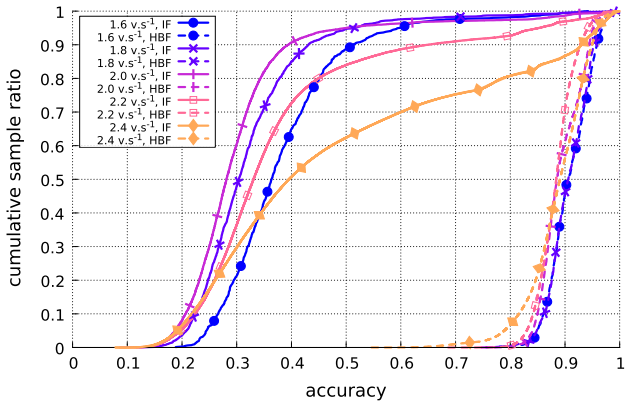


Fig. 6. Accuracy of messages (IF and HBF protocols).

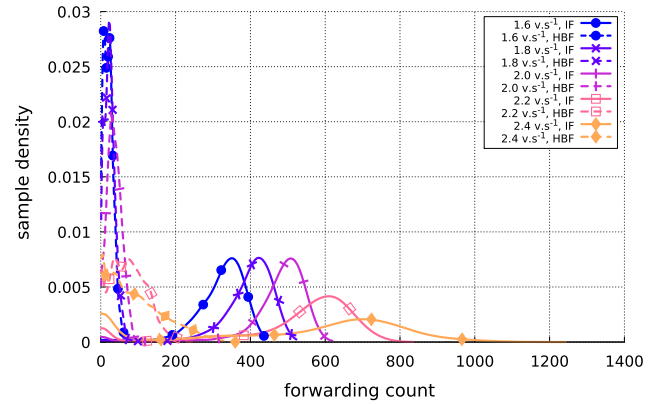


Fig. 8. Distribution of the number of times a message is forwarded (IF and HBF protocols).

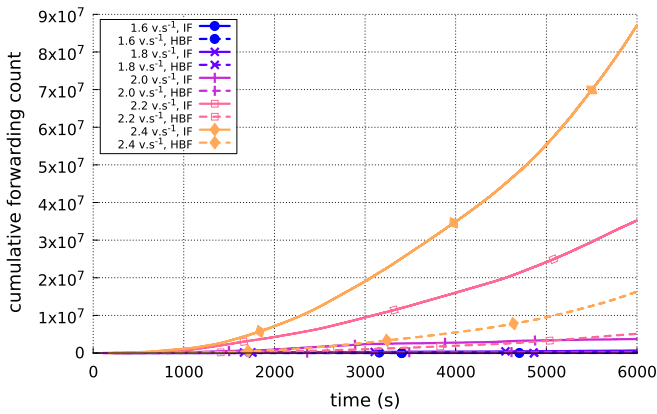


Fig. 7. Number of transmissions as a function of time (IF and HBF protocols).

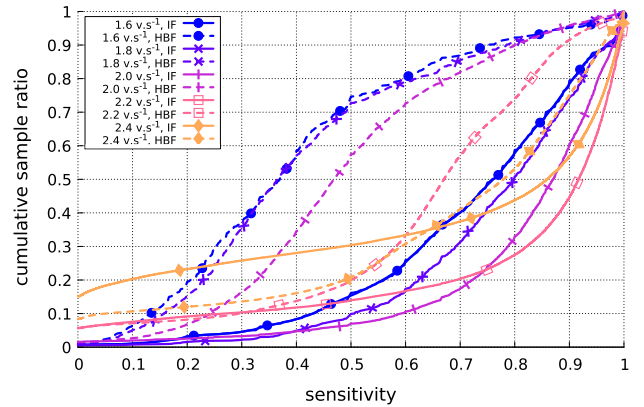


Fig. 9. Message sensitivity (IF and HBF protocols).

forwarding circle. This decision allows a fairer comparison between the two protocols because it isolates the effects of message guiding from the other features.

Simulations were conducted for various densities of traffic obtained by setting the entry flow, which ranged from 1.6 to 2.4 vehicles per second. In our context, these flows were tuned experimentally in order to obtain traffic conditions varying from “almost free” to “very congested”. As shown in Fig. 5, the road network cannot support traffic greater than or equal to 2.2 vehicles per second. Beyond this limit, the congestion provokes an exponential surge of incident reports, as shown in Table 1.

6.5. Experimental results

6.5.1. Accuracy

Fig. 6 shows the accuracy of the communications for the traffic conditions mentioned above. In this diagram, the Y-axis represents the cumulative ratio of messages that reach an accuracy that is less than or equal to the value represented by the X-axis. Almost all the messages transmitted by the HBF protocol reached an accuracy ranging from 0.85 to 1. In contrast, the accuracy of the messages transmitted by improved flooding varied from 0.1 to 1, with very different shapes when the traffic intensity changed.

It is thus clear that the HBF protocol uses the transmission medium very efficiently. Moreover, these results depend very little on the type of traffic (i.e., the overall density of vehicles).

From a general point of view, the transmission of messages tends to become less accurate when the traffic increases, but as

predicted by Eq. (6) this is not true when the wireless medium is saturated (2.2 and 2.4 V/s). We can remark that the HBF protocol is not affected by this phenomenon because it does not overload the wireless medium.

6.5.2. Total number of messages

The message forwarding results confirmed the results from the accuracy study. Fig. 7 shows the cumulative number of messages, as a function of time. One can note that the IF protocol is particularly inefficient. It is also poorly scalable because the message count grew very quickly as the traffic increased. In contrast, the HBF protocol exhibits more favorable behavior because the message count grew slowly, whatever the type of traffic. For example, after 5000 s, the number of messages forwarded was 5 times greater¹² with the IF protocol than with the HBF protocol.

Fig. 8 allows a more quantitative understanding of how partners exchange messages. It shows the distribution of the number of times a message is forwarded. With the HBF protocol, virtually no message was forwarded more than 350 times, and most were forwarded less than 100 times. Moreover, the number of messages forwarded was not very dependent on traffic density. On the contrary, most of the messages transmitted by improved flooding were forwarded between 200 and 800 times, with a maximum value of about 1000 times when the traffic was dense. This point confirms the information given in Fig. 7: the number of messages forwarded

¹² For the 2.4 V/s entry flow, about 5.5×10^7 messages are forwarded by flooding, but only 1.0×10^7 with the HBF protocol.

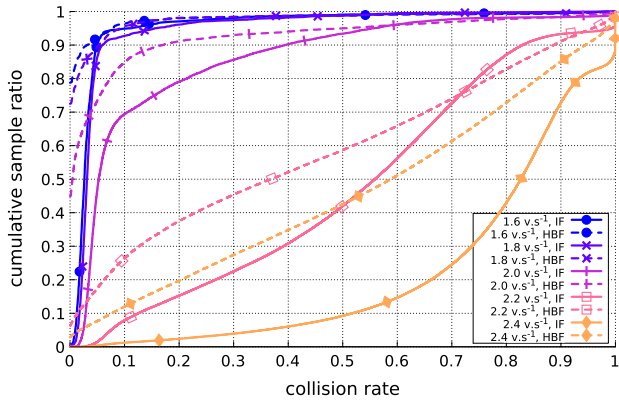


Fig. 10. Data frame collision rate per message (IF and HBF protocols).

provoked by the flooding protocol is very dependent on the overall traffic density. Both diagrams show that the HBF protocol largely outperformed the IF protocol in terms of wireless medium occupation.

6.5.3. Sensitivity

Fig. 9 shows the cumulative percentage of messages for which the sensitivity is less than or equal to a given value, under the same experimental conditions as in the previous section. As one can see, it is no surprise that the transmissions based on improved flooding generally offer excellent sensitivity due to the high redundancy of the transmitted data. This is particularly clear when the traffic is light (1.6 V/s). In this case, for example, 50% of the messages transmitted by flooding exhibited a sensitivity that was less than 0.77. In contrast, 50% of the messages transmitted using the HBF protocol reached a sensitivity that was less than 0.35.

However, this diagram shows very interesting behavior: the sensitivity provided by the IF protocol tended to decrease when the traffic increased. This property is undesirable as the worst sensitivity is observed in a situation where good sensitivity is needed. Conversely, the sensitivity of the HBF protocol tended to improve when the traffic increased. For example, for an overall flow of 2.4 V/s (severe conditions), about 35% of the messages had a sensitivity of less than 0.65 for both protocols.

Below this limit, the sensitivity of the HBF protocol was better than the IF protocol, as well as being much more accurate.

It is important to know the reason why the sensitivity of the IF protocol is poor when the traffic increases. A first clue is given by looking at the origin of the sensitivity curve: for an overall flow of 2.4 V/s, the sensitivity of about 15% of the messages is 0. This means that these messages never reach the immediate neighbors of the primary emitter, probably because the medium was saturated. In order to verify this hypothesis, Fig. 10 represents the cumulative distribution of the data frame collision rate per message. It shows that the collision rate is typically less than 10% and is similar for the two protocols when the traffic is light. When the traffic is high (2.4 V/s), the collision rate deteriorates quickly with the IF protocol; virtually all the data frames collide and 85% of them have a collision rate greater than 60%. Conversely, this deterioration is much slower for the HBF protocol; only 50% of the data frames have a collision rate greater than 60% and a significant proportion of them do not collide.

This observation demonstrates the reality of the problem tackled in this paper. The saturation of the wireless medium could be an issue for the deployment of a FDTIS in an urban environment.

Another way to understand the difference between the two protocols studied is to represent the correlation between the sensitivity (i.e., the true positive rate, TPR) and the fall-out (i.e., the false positive rate, FPR) in ROC space, as shown in Fig. 11. In these

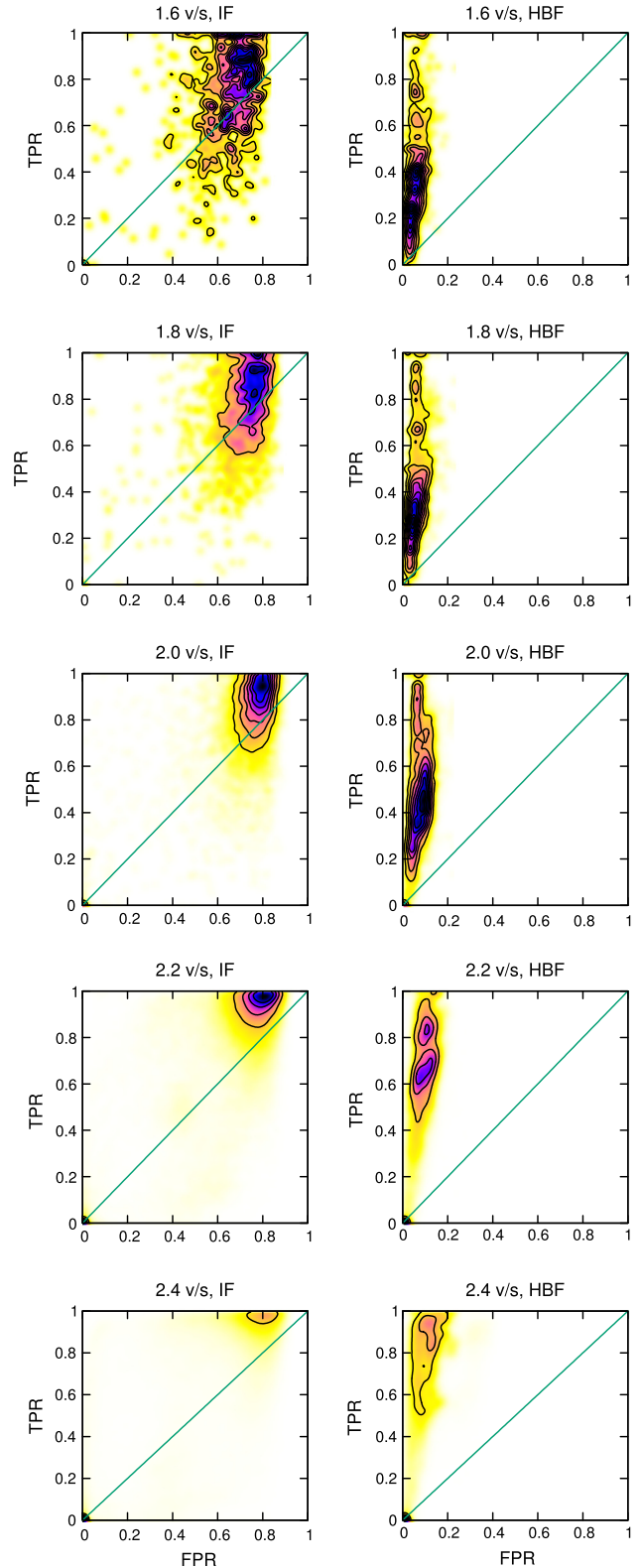


Fig. 11. Correlation between sensitivity and fall-out (IF and HBF protocols).

diagrams, dark tones represent a high density of messages. In ROC space, a system can be considered as excellent when the message density is significant in the upper-left region (high number of true positives, low number of false positives). On the other hand, it is poor when most messages are in the lower right zone (low number of true positives, high number of false positives).

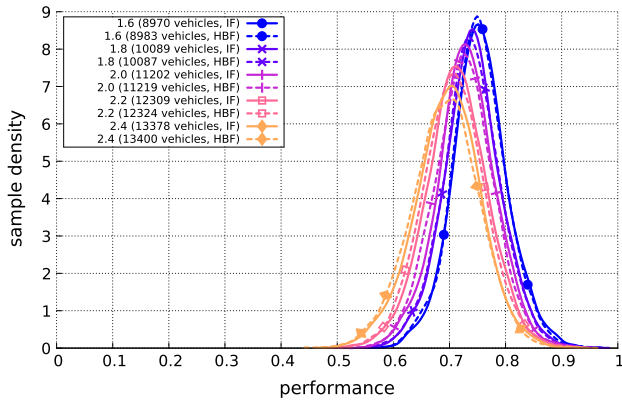


Fig. 12. Distribution of vehicle temporal performances (IF and HBF protocols).

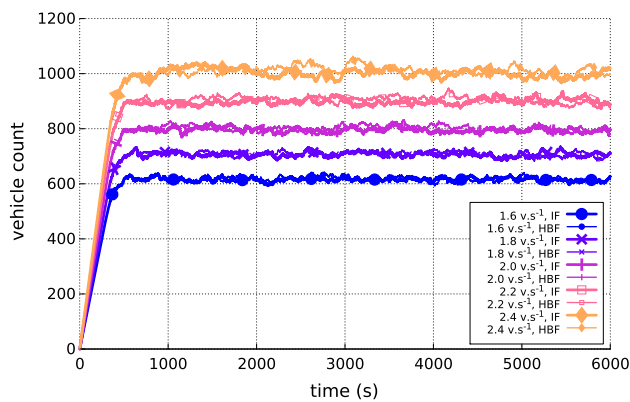


Fig. 13. Number of vehicles on the road as a function of time with periodic re-routing (IF and HBF protocols).

Concerning the IF protocol, one can remark that the true positive rate tended to increase with the traffic, but so did the false positive rate. The correlation between these two indicators shows that vehicles randomly distributed throughout the road network received the messages.

When the HBF protocol was used, the true positive rate was lower, but increased with the traffic: for example, the most frequent rate increased from 0.3 to 0.9 when the traffic varied from “near free” to “very congested”. However, the most important remark is that the false positive rate remained low (about 0.1) regardless of the traffic. This absence of correlation demonstrates that the HBF data routing protocol is particularly efficient for routing messages to the regions where they are useful.

6.5.4. Impact of message routing protocol on the performance of a FDTIS

In order to evaluate the final impact of the proposed protocol on vehicle performance, we measured¹³ this performance using the criterion defined in Section 6.1.4. Fig. 12 presents the results of this evaluation. It shows that the performances were roughly the same despite the fact that the system was generally less sensitive when the HBF protocol was used. Similarly, Fig. 13 shows that the road network is able to absorb the input flows because the number of vehicles varies asymptotically for all cases.

These results prove that the decrease in sensitivity is not great enough to penalize significantly the ability of the system to improve the traffic.

¹³ For this purpose, we re-enabled the capacity of each agent to dynamically compute and use a better route, taking into account the messages it receives.

7. Conclusion

We proposed here an original approach to the problem of wireless medium saturation in FDTIS. Our working assumption was that the vehicles stuck in a traffic jam are representative of the vehicle flows feeding this traffic jam. From this assumption, we proposed a geocasting protocol aimed at guiding the messages to the regions where they are most useful. This protocol, specific to FDTIS, was tested using several criteria, which show that the knowledge of traffic flows based on our hypothesis can very efficiently guide the alert messages. The transmission of useless messages was limited, while the reception rate of useful messages was sufficient to ensure the proper functioning of the system. This result must be viewed as a trade-off as it shows a compromise between two competing criteria (accuracy and sensitivity). The fact that the overall performances of the road guiding system were not affected by the alert messages transmission protocol we proposed demonstrates the quality of this trade-off, the wireless medium being used a lot less.

Moreover, our experiments show that the saturation of the wireless medium is a real issue in the context of FDTIS in an urban environment because it results in degradation of the reception rate in relation to message collisions.

This paper shows that the functioning of a communication network can be optimized on the basis of applicative criteria, if the target application and its circumstances of use are known. However, in term of future prospects, we think that different criteria could be used in different circumstances, for example to transmit alerts via a region where potential partners for message forwarding are sparse. Indeed, such a situation needs strategies based on delay-tolerant routing protocols to be developed that might be very different from the strategies we used in this paper.

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