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Contention-based forwarding with multi-hop connectivity awareness in vehicular ad-hoc networks

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ABSTRACT

Recent vehicular routing proposals use real-time road traffic density estimates to dynamically select forwarding paths. Estimating the traffic density in vehicular ad hoc networks requires the transmission of additional dedicated messages increasing the communications load. These proposals are generally based on unicast sender-based forwarding schemes. The greedy nature of sender-based forwarding can result in the selection of forwarders with weak radio links that might compromise the end-to-end performance. To overcome these limitations, this paper presents TOPOCBF, a novel contention-based broadcast forwarding protocol that dynamically selects forwarding paths based on their capability to route packets between anchor points. Such capability is estimated by means of a multi-hop connectivity metric. The obtained results demonstrate that TOPOCBF can provide good packet delivery ratios while reducing the communications load compared to unicast sender-based forwarding schemes using road traffic density estimates.

1. Introduction

Cooperative vehicular systems, also referred to as Vehicular Ad-hoc Networks (VANETs), are being developed to improve traffic safety and management, as well as providing infotainment applications on the move. To this aim, cooperative systems are based on Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications that allow vehicles and road infrastructure units to exchange information in order to proactively detect dangerous or abnormal road traffic conditions. Cooperative vehicular communications are generally based on the IEEE 802.11p [1] and WAVE (Wireless Access for Vehicular Environments) standards that have also been adapted at European level by the ETSI ITS G5 work item [2].

While certain safety applications rely on single-hop communications, cooperative systems will also benefit from and exploit the capability to communicate with distant vehicles and infrastructure nodes through multi-hop transmissions. Multi-hop communications would help notifying the occurrence of abnormal situations (e.g. road traffic accidents or congestion events) so that drivers have sufficient time to react and avoid them. For example, vehicles that are moving towards a highway congested area could avoid it if they received the notification before the nearer highway exit. Despite its possible benefits, it is important noting that the effectiveness of multi-hop vehicular communications strongly depends on the employed routing protocol and VANETs' unique features, e.g. high vehicular mobility or challenging propagation conditions. Vehicular routing protocols generally use position-based (or georouting) techniques that select the forwarding nodes based on their geographical position. To this aim, vehicles obtain their position from on-board GPS devices, and those of neighboring vehicles through the periodic

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exchange of beacon messages.[1] Recent georouting proposals dynamically select forwarding routes based on real-time traffic estimates. To this aim, the techniques try to detect road segments characterized with a high vehicular density[2] in order to ensure the presence of sufficient relaying nodes. Routing protocols generally use greedy sender-based forwarding schemes where vehicles unicast the packet to be forwarded to the neighbor vehicle that provides the highest progress towards the final destination. However, it is important noting that the real-time and distributed estimation of vehicular density over entire road segments generally requires transmitting additional and dedicated messages, thereby increasing the communications load [5]. Moreover, greedy sender-based forwarding schemes can result in the selection of forwarders with weak radio links to the transmitting vehicles. In this context, countermeasures to increase the transmission reliability might be necessary at the expense of communications overhead or design complexity [6]. To overcome these limitations, this paper presents TOPOCBF (Road Topology-Aware Contention-Based Forwarding), a novel broadcast contention-based forwarding protocol that dynamically selects the forwarding road segments based on their multi-hop connectivity. The use of multi-hop connectivity allows selecting routing paths with high probability to forward the message towards the destination. In addition, multi-hop connectivity can be obtained at a lower communications load cost than vehicular traffic density [5]. Broadcast schemes have been previously proposed to disseminate information over a target area (e.g. [7,8]). Instead, TOPOCBF exploits the capability of broadcast contention-based forwarding schemes to reliably forward messages to relay nodes in the path towards a geo-referenced destination. As this study will demonstrate, TOPOCBF can provide good packet delivery ratios with a low communications overhead cost that reduces the probability of communications congestion.

2. State of the art

Vehicular position-based routing generally relies on the greedy forwarding approach in which forwarding nodes are selected according to their capability to provide a higher progress towards the final destination. The Greedy Perimeter Stateless Routing (GPSR) [9] and the Contention-Based Forwarding (CBF) [10] are classical examples of protocols adopting greedy forwarding. Greedy forwarding schemes may suffer the so-called "local maximum" problem every time a packet reaches a node that has no neighbors offering more progress to the destination. This problem can be particularly relevant in urban scenarios where the presence of buildings can hide best possible local forwarders, and hence generate situations of local maximum with higher frequency [11]. In this case, a protocol might try to recover the packet forwarding at the expense of additional overhead, or drop the packet and consequently reduce the end-to-end delivery performance. To overcome these limitations, map-assisted protocols like Spatially Aware Routing (SAR) [12] extend the greedy forwarding scheme by targeting vehicles placed at specific intermediate road intersections. In fact, propagation conditions are more favorable for vehicles located at intersections that can more reliably select the next packet forwarder. However, SAR selects the set of relaying intersections based on the shortest distance between source and destination, and does not consider the actual presence of possible forwarding vehicles thereby increasing the risk of packet droppings at intersections. In this context, the study reported in [13] highlighted how uneven distributions of the road traffic over different streets can affect the delivery performance of vehicular routing protocols, and proposed the A-STAR (Anchor based Street and Traffic Aware Routing) technique. A-STAR tries to overcome the SAR inefficiencies by routing packets along roads with high vehicular density, which increases the probability of finding packet forwarders, and thereby the end-to-end delivery performance. Vehicle-Assisted Data Delivery (VADD) [14] further improves A-STAR's approach by assuming the use of digital maps and GPS systems providing a time-variable characterization of the vehicular density based on traffic statistics. Using this characterization, the VADD routing protocol tries to compute the most reliable forwarding paths in terms of probability to find a forwarding vehicle. Although this approach is valid on average, the use of traffic statistics cannot provide accurate real-time information on the multi-hop connectivity of road segments, in particular if unexpected changes in the distribution of road traffic flows occur. Proposals like Landmark Overlays for Urban Vehicular Routing Environments (LOUVRE) [15] can handle these situations by making use of real-time traffic information. In LOUVRE, vehicles assess the real-time traffic density of the road they are placed in, and proactively disseminate this information through periodic messages to obtain a shared density map of the entire network. To keep up-to-date the traffic density information, a considerable amount of overhead is required. SADV (Static-node Assisted adaptive Data dissemination protocol for Vehicular networks) [16] solves this problem by routing packets through static nodes placed at each road intersection. Estimations of the delay needed for a packet to be forwarded between two adjacent intersections are disseminated by vehicles so that the protocol can compute up-to-date forwarding paths able to account for instantaneous changes in traffic flow distribution. Despite this adaptive ability, SADV is based on the unrealistic assumption that static nodes will be deployed at every intersection. The Improved Greedy Traffic Aware Routing protocol (GyTAR) [17] proposes a different approach where the routing path is dynamically updated as the packet is forwarded towards

[1] At European level, ETSI ITS work group 3 is defining the beacons as network layer messages containing a geo-networking header that allows nodes to periodically advertise their position to their neighbors [3]. In addition, the vehicles' position information is also exchanged by means of periodic Cooperative Awareness Message (CAM) [4]. CAM payload contains all the information needed to run cooperative vehicular safety applications. As a result, CAM messages will be transmitted at shorter intervals compared to beacon messages. The IEEE 802.11p/WAVE standards do not define a network layer beacon message. Instead, vehicles exchange their position through the transmission of periodic Basic Safety Messages (BSMs) defined by the SAE J2735 standard.

[2] In this paper, vehicular density refers to the traffic density of a road segment, and not to the local density that a vehicle might estimate through the beacon messages received from neighbor vehicles.

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the final destination. Every time a packet is received at a road intersection, GyTAR computes the next forwarding intersection considering its progress towards the final destination, and also the estimated real-time vehicular density along the road segment leading to it. To compute the density, GyTAR adopts IFTIS (Infrastructure-Free Traffic Information System) [18], a fully distributed algorithm using dedicated multi-hop transmissions. Similarly to GyTAR, the Reliable Inter-VEhicular Routing (RIVER) protocol [19] uses probe messages to actively monitor at road intersections whether adjacent road segments allow reliable multi-hop transmissions. RIVER also defines a passive monitoring system through which vehicles acquire information about the forwarding capability of distant road segments. This information is contained in routing packets that have been forwarded over those road segments. The Intersection-based Geographical Routing Protocol (IGRP) [20] complements the estimations of routing paths' capability to reliably multi-hop forward information with the quality of service (QoS) of vehicular applications. The proposal makes use of a central control unit that collects mobility information from vehicles, and employs genetic algorithms to compute in real-time optimal forwarding paths also considering QoS constraints. The computed paths are then communicated to vehicles on demand through multi-hop transmissions. The conducted review has shown that distributed monitoring systems used to support routing decisions are generally based on the real-time estimation of the vehicular density of forwarding paths. However, these solutions require the transmission of dedicated messages, thereby increasing the communications load and channel congestion probability.

Most of the discussed protocols adopt a sender-based forwarding approach in which packets are unicasted to the node exhibiting the highest progress towards the final destination. While this approach can reduce the latency and number of hops to reach the final destination, the selection of forwarders that provide the highest progress towards the final destination increases the distance between the forwarding and preceding nodes, and can hence result in unreliable or unstable radio links [6]. Such instability may increase the overhead due to retransmissions, as well as require additional protocol complexity in order to detect reliable links able to guarantee an adequate performance. In contention-based forwarding schemes, packets are forwarded through broadcast transmissions. When receiving a packet, nodes activate a distributed contention mechanism to determine the next forwarder. Although contention-based forwarding forces multiple nodes to receive and process the same packet, it also ensures that at least one of them will retransmit the packet, thereby reducing the probability of packet dropping. Due to its broadcast nature, contention-based forwarding has been mostly adopted for information dissemination over target areas; the Urban Vehicular BroadCAST (UV-CAST) [7] and the Acknowledged Broadcast from Static to highly Mobile (ABSM) [8] protocols are two recent examples. However, contention-based forwarding provides advantages for multi-hop routing in VANETs as demonstrated in [6]. Protocols like CBRP (Contention Based Routing Protocol) [21] and CLA-S (Connection-less Approach for Streets) [22] have applied contention-based routing in urban environments. Inspired from [16], CBRP assumes that vehicles are informed about reliable forwarding paths by fixed static nodes deployed at every intersection, which is highly unrealistic. On the other hand, CLA-S introduces the concept of 'forwarding area' as a set of streets and intersections where packets are intentionally replicated. This replication increases the chances to find a multi-hop connected path to the final destination, but also the communications load. More recently, the Beacon-less Routing Algorithm for Vehicular Environments (BRAVE) [23] has proposed the adoption of contention-based broadcast retransmissions over routes computed using the Dijkstra algorithm and eventually additional static information (e.g. road vehicular density). No real-time traffic monitoring is assumed to evaluate the actual forwarding capability of the selected routes. To cope with possible disconnections in the selected forwarding paths, BRAVE adopts a store, carry and forward mechanism.

3. The TOPOCBF approach

The existing proposals base their routing decisions on real-time road traffic density estimates. Using such estimates to select forwarding paths can help selecting the paths with a higher number of vehicles. If all vehicles apply the same routing policy, all packets will be forwarded over the routes with a higher vehicular density, thereby increasing the already high communications channel load in these routes. Augmenting the channel load increases the probability of channel congestion, and therefore decreases the end-to-end delivery performance. In addition, it is important noting that two road segments with different traffic densities might both be able to multi-hop forward a packet from one end of the segment to the other end if there are sufficient spatially distributed vehicles to do so. The capability to multi-hop forward packets in one road segment is therefore not directly dependent on its vehicular traffic density but rather on its multi-hop connectivity. In this context, and differently from existing proposals, TOPOCBF dynamically selects the next road segment over which to forward packets based on their multi-hop connectivity rather than on their vehicular density. A road segment is here defined to be multi-hop connected if it contains a sufficient number of spatially distributed vehicles to multi-hop forward packets from one end of the road segment to the other end. TOPOCBF obtains the real-time multi-hop connectivity information using the DiRCoD (Distributed and Real Time Communications Road Connectivity Discovery) scheme presented in [5]. DiRCoD estimates the multi-hop connectivity of road segments using a virtual distance metric that indicates whether it is possible to find sufficient vehicles to multi-hop forward a packet from one end of the road segment to the other end. If it is not possible to find sufficient vehicles, the metric quantifies the closer distance to the target intersection at which packets could be multi-hop forwarded. As detailed in [5], multi-hop connectivity estimates can be obtained at a much lower communications overhead cost than traffic density estimates. In addition, forwarding packets based

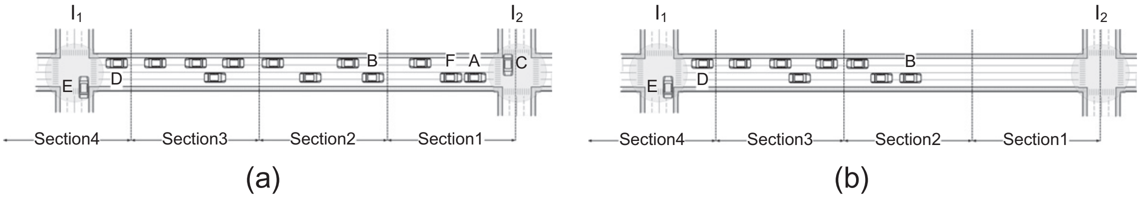

Fig. 1. Road segment with DiRCoD full multi-hop connectivity (a), and DiRCoD partial multi-hop connectivity (b).

on the multi-hop connectivity of road segments can help distributing the communications load over the road network, and avoid overloading the densest road segments.

TOPOCBF forwards packets over selected road segments using contention-based broadcast communications. Contention-based broadcast forwarding can increase the packet forwarding reliability compared to unicast schemes that can be more influenced by radio propagation effects between transmitting and receiving nodes [6]. This reliability is obtained at the expense of a higher probability to flood the network with redundant packet duplicates [11]. However, this paper will show that such flooding effect is avoided with TOPOCBF by limiting the broadcast forwarding process between the two intersections that define a road segment.

3.1. DiRCoD

To compute the multi-hop connectivity of a road segment, DiRCoD uses periodic standard beacon messages [3]. To explain DiRCoD's operation, let us consider the scenario depicted in Fig. 1 where a road segment is delimited by two intersections I_1 and I_2. In the depicted scenario, vehicle E entering I_1 needs to be informed about the connectivity status of the road segment in the direction of I_2 (direction $I_1 \rightarrow I_2$ in the following) to decide whether it is convenient to forward a packet in this direction or not. A road segment is here defined to be multi-hop connected if it contains a sufficient number of spatially distributed vehicles to multi-hop forward packets from one end of the road segment to the other end. If this is the case (Fig. 1a), the packet would be forwarded directly to I_2 through multi-hop transmissions. In case of partial multi-hop connectivity (Fig. 1b), a packet transmitted from I_1. could not be multi-hop forwarded up to I_2, and would only reach a vehicle placed at a given distance from I_2. To quantify this remaining distance and thereby the connectivity status of a road segment, DiRCoD defines the *virtual distance* metric separating I_2 from I_1 (the lower the virtual distance, the better the multi-hop connectivity). To estimate the *virtual distance*, DiRCoD considers that the road segment is divided into road sections numbered with increasing values as their distance to I_2 increases (see Fig. 1). Each road section has the same length that is actually equal to the vehicles' communications range.[3] Formally, DiRCoD defines the *virtual distance* as the number of road sections (or hops) between I_2 and the closest vehicle to I_2 that can be reached from I_1 through multi-hop transmissions. In Fig. 1b, DiRCoD's *virtual distance* evaluated at I_1 is 2 hops since a packet transmitted from I_1 would only reach vehicle B that is placed at 2 hops from I_2. On the contrary, Fig. 1a illustrates a road segment with full multi-hop connectivity. In this case, the *virtual distance* separating I_2 from I_1 is 0 since a packet can multi-hop forwarded from I_1 to I_2.

To inform vehicles entering an intersection (I_1 in the example shown in Fig. 1) of the connectivity status of a road segment ($I_1 \rightarrow I_2$ in the example shown in Fig. 1), DiRCoD includes this status information into a small "*Connectivity Field*" (*CF*) that is added to the beacon messages periodically transmitted by vehicles every T_{Beacon} seconds.[4] A vehicle appends a *CF* indicating the road section it is placed at, unless it detects (by consulting its neighbor table) that other vehicles are located at road sections closer to I_2 or are in the intersection zone of I_2 (intersection zones are circular regions centered at road intersections). In the scenario depicted in Fig. 1b, vehicle B does not detect any other vehicle closer to I_2. As a result, once the periodic timer T_{Beacon} expires, it generates and appends to its beacon message a *CF* indicating a *virtual distance* of '2' (two hops are necessary to reach vehicles in I_2's intersection zones). In the scenario depicted in Fig. 1a, vehicle F would initially append a *CF* with a *virtual distance* of '1' to its beacon messages since it is located in Section 1. However, since vehicle F can detect the presence of vehicle C at I_2 (it is within its communication range, and thereby is listed in its neighbor table), it generates and appends to its beacon a *CF* indicating a *virtual distance* of '0' upon receiving a beacon from vehicle C. Similarly, vehicle B placed at section 2 in Fig. 1a would initially append a *CF* of '2' in its beacon messages. However, after detecting the presence of vehicle F and receiving its beacon message with a *CF* equal to 0, vehicle B also appends a *CF* of '0' to its own beacon message. Through this sequential process, the *CF*s are forwarded towards I_1. Vehicles placed at I_1 will receive a beacon message with a *CF* of '0' indicating full multi-hop road connectivity in Fig. 1a, and a *CF* of '2' indicating partial multi-hop connectivity (the closest vehicle to I_2 is two hops away from the intersection) in Fig. 1b.

[3] For a realistic propagation channel, it is not possible to deterministically define a fixed communications range. The capability for two nodes to successfully communicate with each other at a given transmission power and distance can only be described in a probabilistic way. In this context, the length of DiRCoD's road sections has been defined in this work as the distance at which two vehicles in line of sight propagation conditions successfully exchange 99% of the transmitted beacons.

[4] In [5], the authors describe how the size of a CF can be limited to a few bits (e.g. one byte). Since DiRCoD is simultaneously run for both directions of a road segment, one bit in the *CF* always represents the direction of the connectivity assessment. The rest of the bits are used to code the *virtual distance*. A vehicle receiving a *CF* at an intersection uses the position of the transmitting vehicle (included in the beacon message) to understand to which road segment the *CF* refers to.

If all vehicles along a road segment appended a *CF* to their beacons, DiRCoD would generate redundant connectivity estimates which could compromise its scalability. To limit the inclusion of *CF*s in beacon messages, a distributed mechanism is adopted through which only a minimum set of vehicles generates and forwards connectivity fields (more details can be found in [5]). Moreover, DiRCoD defines a method [5] to control the period between two consecutive road connectivity assessments. Such period is referred to as "*Connectivity Field generation period*", and indicates the time that vehicles have to wait before generating or forwarding new *CFs*. If the road traffic does not vary very rapidly, the connectivity status of a road segment stays stable for a few seconds. As a result, the *CF generation period* can be set to higher values so that connectivity estimates are generated with lower frequency.

In [5], the authors demonstrated that DiRCoD provides accurate and up-to-date multi-hop road connectivity estimates while limiting the communications overhead. The results reported in [5] were obtained under simplified propagation conditions with fixed and deterministic communication ranges. However, radio links are characterized by rapidly varying signal levels as a result of multipath fading. In this context, beacon messages could be instantaneously transmitted between two vehicles without being able to guarantee a reliable link between them, which could in turn provide incorrect estimates of the DiRCoD multi-hop connectivity of a road segment. To address this issue, a reliability mechanism has been added to DiRCoD in this work. In particular, a DiRCoD's *CF* is generated or forwarded only if beacons are received from reliable neighbors. This work considers a beaconing rate of 2 Hz (and hence a T_{Beacon} of 0.5 s). In this context, a neighbor is considered to be reliable if at least 2 of its beacons have been received in the last 4 s, and the last beacon reception is not older than 1 s. In this context, it is important demonstrating that the enhanced DiRCoD scheme can maintain the benefits reported in [5] under realistic radio propagation conditions including the effects of path-loss, shadowing and multipath fading. To this aim, a new performance analysis comparing DiRCoD and IFTIS [18] is here reported.

Differently from DiRCoD, IFTIS estimates the connectivity of a road segment by computing its vehicular density using dedicated geounicast messages called *Cell Density Packets* (*CDPs*). Considering the scenario depicted in Fig. 1, *CDPs* are originated by vehicles traveling from I_1 to I_2 when they reach the intersection I_2. The *CDPs* are multi-hop transmitted towards I_1 so that forwarding vehicles can estimate the vehicular density in adjacent portions (cells) of the road segment, and accordingly update the *CDP* before retransmitting it.[5] When finally reaching I_1, the *CDP* contains the overall cumulated road density. At I_1, the *CDP* is broadcasted, so that vehicles crossing I_1 are informed about the density of the road segment. To control the communications overhead, the *CDPs* are only originated at I_2 by those vehicles that previously retransmitted *CDPs* along the road segment. As a result, the generation of *CDPs* and the consequent rate at which the road density estimates are updated, are dependent on how smooth is the road traffic flow.

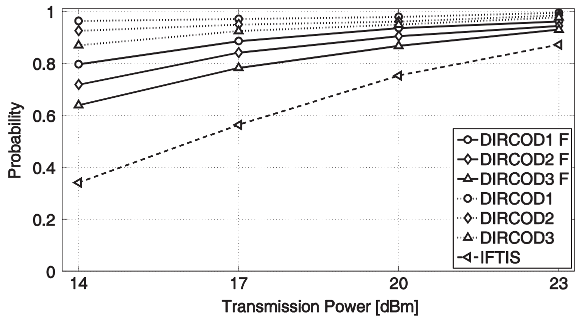

Fig. 2. Probability of receiving at least one connectivity estimate at I_1.

The results shown in Figs. 2–4 refer to a single road segment (like Fig. 1) included in a Manhattan-like road network. The road segment is 500 m long, and has one lane per direction and two intersection zones with a radius of 30 m at its end points. The average vehicular density is 10 vehicles/km/lane. Vehicles communicate using the 5.9 GHz ETSI ITS G5A radio interface (the European adaptation of IEEE 802.11p) with a transmission power that is varied to investigate its impact on the protocols' performance. It is important to highlight that while DiRCoD can report at I_1 *CFs* under partial and full multi-hop road connectivity connections (Fig. 1b and Fig. 1a), IFTIS can only deliver *CDPs* at I_1 when the road is fully connected Fig. 1b. For a fair comparison between both techniques, DiRCoD is also evaluated with regards to its capability to detect only situations of full connectivity ("DiRCoD F" in the figures). Fig. 2 depicts the probability that vehicles located at I_1 receive before leaving the intersection zone at least one road connectivity estimate using DiRCoD's *CFs* or IFTIS' *CDPs*. This metric represents the techniques' ability to provide vehicles at intersections with up-to-date road connectivity information in order to be able to decide in real-time the road segments over which they should forward routing packets. The results show that DiRCoD always achieves a higher probability to provide connectivity estimates at road intersections, even if only situations of full connectivity were to be detected. The results depicted in Fig. 2 show that DiRCoD always performs better than IFTIS, independently of DiRCoD's *CF generation period* ("DiRCoD x" refers to a *CF generation period* of x seconds) and the transmission power. This is due to the fact that DiRCoD uses periodic beacon transmissions. As a result, DiRCoD estimates are delivered at I_1 with more regularity and higher frequency compared to IFTIS. On the other hand, IFTIS generates *CDPs* only when previous *CDP* forwarders arrive at intersection I_2. This occurs with irregular periodicity and depends on traffic flow variations. As a result, IFTIS estimates are less frequently delivered to I_1, thereby increasing the risk of using outdated density information when a vehicle has to decide at I_1 over which road segment to forward a routing packet. To better analyze this

[5] IFTIS' cells are defined as partially overlapping circles distributed along the road and with radius equal to the vehicle's communications range. For consistency and fair comparison, this radius has been here set as the inter-vehicle distance ensuring a 99% of probability to successfully exchange beacons.

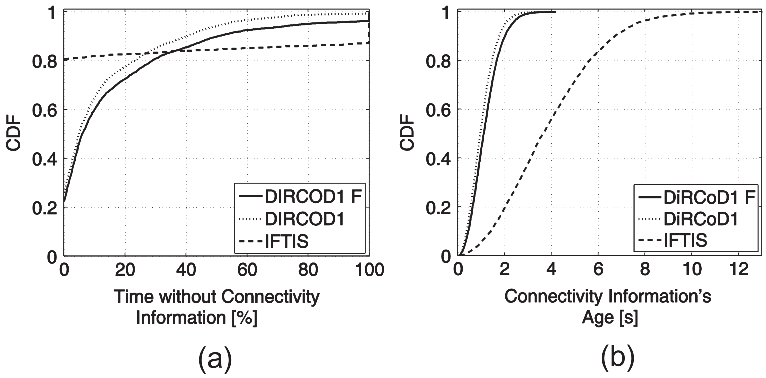

Fig. 3. CDF of the time spent at I_1 before receiving a connectivity estimate (a) and CDF of the age of the connectivity estimate hold at I_1 (b) (23 dBm transmission power).

effect, Fig. 3a represents the cumulative distribution function (CDF) of the percentage of time that a vehicle spends at I_1 before receiving the first connectivity estimate; the depicted results were obtained for a 23 dBm transmission power. It is important noting that this time percentage should be kept as low as possible since vehicles would have no information to drive possible routing decisions during this period. Fig. 3a shows that using IFTIS, 80% of vehicles already received a *CDP* when entering I_1. On the other hand, DiRCoD results in that 80% of vehicles can spend up to 23% of time at the intersection before receiving the first *CF*. IFTIS better performance is due to the fact that since *CDPs* are broadcasted after arriving at I_1, most vehicles receive them before entering I_1. In order to understand to what extent the connectivity information that vehicles hold at I_1 is up-to-date, and therefore represents the actual connectivity status of the road segment, Fig. 3b shows the CDF of the age (in seconds) of the connectivity information that vehicles have when getting at the center of I_1. The depicted results show that the age of DiRCoD's *CFs* is generally much lower than that of IFTIS' *CDPs,* and in no case higher than 4 s. On the other hand, IFTIS results in much older connectivity information (up to 12 s old as shown in Fig. 3b) that may not be useful for routing decisions.

Besides measuring the ability to provide vehicles at intersections with up-to-date road connectivity information, it is also important to evaluate the amount of communications resources required by DiRCoD and IFTIS. Fig. 4 represents the average communications overhead generated by both techniques over a time range of 1 s.[6] The overhead corresponds to the amount of bytes needed to estimate multi-hop connectivity or road traffic density. The results clearly show that DiRCoD's connectivity discovery mechanism generates a much lower (two orders of magnitude) communications overhead than IFTIS. This is due to the fact that while DiRCoD just adds one byte information to a very limited amount of standard beacon messages, IFTIS uses dedicated geo-unicast messages. As Fig. 4 shows, DiRCoD's overhead can be further reduced by increasing the *CF generation period* without significantly decreasing the probability of receiving updated road connectivity information at I_1 (Fig. 2). These results clearly indicate that the multi-hop connectivity of road segments can be efficiently estimated using DiRCoD.

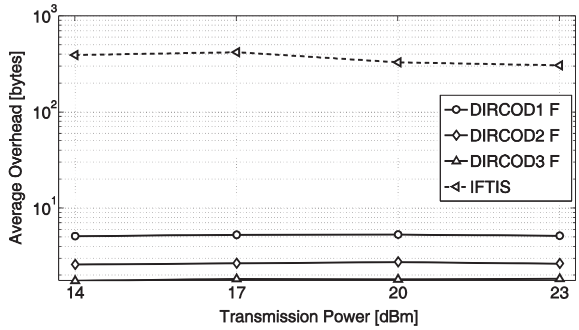

Fig. 4. Average overhead over 1 s.

3.2. TOPOCBF

As a contention-based forwarding scheme, CBF [10] uses broadcast transmissions to forward packets. Upon receiving a packet, nodes activate a timer called "*forwarding timeout*", that when expired triggers the packet retransmission. The duration of the *forwarding timeout* at each node is inversely proportional to the progress of the node towards the final destination. As a result, the closest node to the destination retransmits first the packet, and when the other nodes overhear the retransmission, they cancel their forwarding attempt. Forwarding packet duplicates is also avoided by identifying packets through an ID. The results reported in [6] showed that CBF achieves higher packet delivery ratios than simple sender-based forwarding schemes. As the authors point out, sender-based schemes transmit over unreliable links, and thereby may require several transmission attempts to overcome packet transmission errors. Despite its higher performance, [11] showed that CBF can result in packet duplications at road intersections in urban environments due to visibility and propagation conditions; packet duplications increase the

[6] The overhead values of DiRCoD are very similar to those of DiRCoD F. They have been omitted to ease the readability of the figure.

communications overhead. To overcome this inefficiency and reduce the communications overhead, this paper presents TOPOCBF, an evolution of the CBF protocol that exploits DiRCoD's real-time connectivity information in its dynamic routing decisions.

TOPOCBF adopts CBF's broadcast greedy forwarding approach as well as its contention-based mechanism. However, and differently from CBF, TOPOCBF dynamically selects at intermediate anchor points (in this case, intersections) the next road segment over which to forward the packet to be routed to the final destination; the selection is based on DiRCoD's multi-hop connectivity estimates. The process to select the subsequent intersections, or anchor points, will be repeated until the packet reaches the final destination. Once a forwarding road segment is selected, TOPOCBF uses a broadcast greedy forwarding scheme to reach the closest vehicles to the center of the next intersection. In fact, vehicles placed at an intersection have a better knowledge of the connectivity status of adjacent road segments, and consequently, can select the next anchor point more efficiently. To reach those vehicles, TOPOCBF operates a contention-based scheme that requires the knowledge of the geographical coordinates of the next intersection (obtained through GPS and digital maps). These coordinates are then included in the forwarded packets using an additional "*next intersection field*".

To illustrate the operation of TOPOCBF, let us consider the scenario depicted in Fig. 5 where vehicle B at intersection Int1 has to select the next road segment (and thereby target intersection) over which to route a packet towards the final destination D. Among the candidate target intersections, TOPOCBF selects the most appropriate one by analyzing the following properties:

- *Property 1: Progress towards the final destination.* Only intersections providing progress towards D are considered (e.g. intersections Int2 and Int3 in Fig. 5).
- *Property 2: Freshness of the road connectivity information.* Vehicle B continuously processes the received beacons to retrieve the connectivity status of adjacent road segments contained in DiRCoD's *connectivity fields* (*CFs*). It then checks the time at which the last*CF* referring to the intersections holding *property 1* was received. If the received *CF* information is older than a threshold referred to as "*Connectivity Expiry Time*" (*CET*), vehicle B considers that the road segment leading to the intersection under evaluation does not guarantee an adequate multi-hop connectivity. As explained in Section 3.1, in case of full or partial multi-hop road connectivity, a vehicle placed at an intersection receives a beacon message with the *CF* information appended at least every *CF generation period* seconds. The absence of *CF* receptions for longer periods than the *CF generation period* might imply that the corresponding road segment does not currently offer either full or partial connectivity. As a result, vehicle B would consider as viable candidate anchor points or intersections only those for which the last *CF* has been received within the last *CET* seconds (with *CET* $\geqslant$ *CF generation period*). If none of the candidate intersections satisfies *properties 1* and 2, the packet to be routed gets dropped. Otherwise, a third property should be considered.
- *Property 3: Road connectivity status.* If more than one candidate intersection satisfies *properties 1* and 2, vehicle B will select as the next target intersection to which forward the packet the one characterized by the lower DiRCoD *virtual distance*. As it was explained in Section 3.1, DiRCoD *virtual distance* provides an indication of the multi-hop connectivity of road segments in a specific direction: the lower the *virtual distance*, the closer to the target intersection can packets be multi-hop forwarded. If finally two or more candidate road intersections are characterized by the same minimum *virtual distance*, the vehicle will select one of them randomly.

Once TOPOCBF selects the next target intersection, and consequently the road segment over which the routing packet has to be forwarded, vehicle B includes its coordinates in the *next intersection field* and rebroadcasts the packet. Among the vehicles receiving this packet, only those providing progress towards the targeted intersection will activate a *forwarding timeout*. Let us suppose that the selected next target intersection is Int2, and that (among the other nodes) vehicle E receives the forwarded packet from vehicle B. As represented in Fig. 6 (an enlargement of Fig. 5) TOPOCBF's *forwarding timeout* t_E (in seconds) is

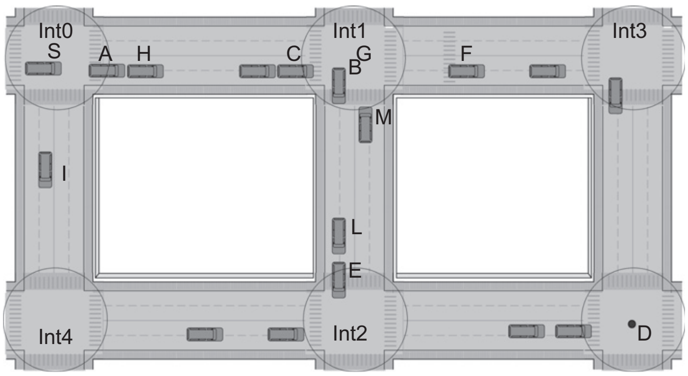

Fig. 5. Urban scenario.

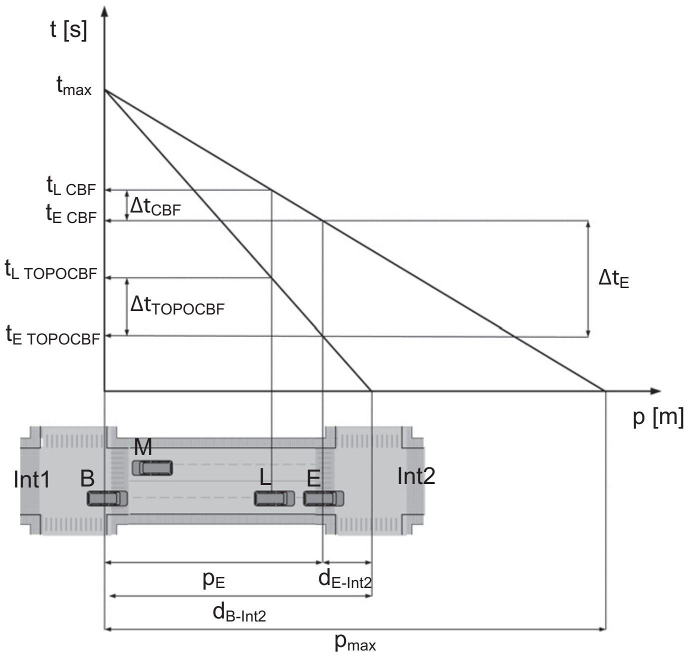

Fig. 6. TOPOCBF and CBF *forwarding timeout*.

computed based on the progress p_E (in meters) of vehicle E towards the target intersection Int2:

$$t_E = \begin{cases} t_{\max}\left(1 - \frac{p_E}{p_{\max}}\right) & \text{if } d_{B-Int2} > p_{\max} \\ t_{\max}\left(1 - \frac{p_E}{d_{B-Int2}}\right) & \text{otherwise} \end{cases} \quad (1)$$

where $p_{\max}$ (in meters) is equal to the maximum distance at which a vehicle is expected to receive packets from vehicle B, $t_{\max}$ (in seconds) is the maximum *forwarding timeout* duration defined by the protocol, and the progress p_E is computed as:

$$p_E = d_{B-Int2} - d_{E-Int2} \quad (2)$$

with d_{B-Int2} and d_{E-Int2} representing the distance (in meters) separating vehicles B and E from Int2, respectively. If vehicle E detects that d_{B-Int2} is higher than p_{max}, the computed *forwarding timeout* t_E is equal to that estimated by the original CBF protocol. If this is not the case, the maximum progress that vehicle E can provide towards the next intersection is bounded to the distance d_{B-Int2}. To better understand the differences between TOPOCBF and CBF, the functions adopted for the computation of their respective *forwarding timeouts* are graphically represented in Fig. 6. TOPOCBF computes the *forwarding timeout* considering the progress towards the next target intersection instead of towards the final destination. As a result, its *forwarding timeout* on vehicle E can be Δt_E seconds shorter than for CBF as in the example illustrated in Fig. 6, which thereby can reduce the end-to-end delivery latency.

The operation of TOPOCBF, and in particular the fact that it forwards packets towards next target intersections rather than the final destination, requires the implementation of a different policy to discard packet duplicates compared to CBF. Let us suppose that a packet forwarded by a vehicle (vehicle S in Fig. 5) in a given road segment is received by a vehicle (vehicle M in Fig. 5) placed in an adjacent road segment beyond the current target intersection (Int1 in Fig. 5). Since vehicle M is not the closest vehicle to the target intersection, it would not initially forward the packet received from vehicle S. Based on TOPOCBF's operation, the packet will be retransmitted instead by vehicle B, which is very close to the center of Int1's intersection zone. After this retransmission, vehicle M may receive the same packet it previously received from vehicle S. If the CBF policy to discard packet duplicates was applied, vehicle M would check the packet's ID and discard it since it had already received it. However, in the case of TOPOCBF and the example illustrated in Fig. 5, the new target intersection is Int2 and vehicle M provides a progress towards Int2. As a result, the second packet reception at vehicle M should not be discarded since vehicle M is a candidate node to forward the packet towards Int2. To avoid inadequately discarding packet duplicates that are beneficial to TOPOCBF's operation, nodes keep track not only of the ID of received packets, but also of their *next intersection field*. A packet duplicate is discarded only if a packet carrying the same ID and *next intersection field* has been received before.

Radio propagation effects have been shown to influence the operation and performance of CBF [11]. To illustrate some of these effects, and show how TOPOCBF can better address their negative impact, let us consider the scenario illustrated in Fig. 5 where vehicles A, H and B receive from vehicle S a routing packet with final destination D, and having Int1 as the next targeted intersection. When vehicle B retransmits the packet first, the radio signal variability characteristic of the multipath fading might result in that one of the vehicles A or H does not overhear it. In this case, the missed suppression of a *forwarding timeout* generates an unnecessary and unwanted packet duplicate. In the unfortunate case that both vehicles A and H do not overhear the packet's retransmission and are very close to each other, their *forwarding timeouts* will have almost equal duration. As explained in [10], if the difference between the *forwarding timeouts* on two or more nodes is lower than a minimum time needed for suppression, then the nodes deliver the packet to their MAC (Medium Access Control) layer at almost the same time, and both transmit redundant packet duplicates. As previously explained, TOPOCBF estimates the *forwarding timeout* using the next target intersection rather than the final destination, which increases the likelihood of having different timeouts for competing forwarders compared to CBF ($\Delta t_{TOPOCBF} > \Delta t_{CBF}$ in Fig. 6). Consequently, the design of TOPOCBF can help reducing the occurrence of multiple packet duplicates. As shown in [11], packet duplicates can also occur at urban intersections due to the presence of buildings blocking the radio signals. To illustrate this effect, let us consider in Fig. 5 that vehicles G and I receive a packet from vehicle S to be retransmitted using CBF. Since vehicle G provides a higher progress towards the final destination than vehicle I, it would retransmit first. However, the presence of buildings might prevent vehicle I from overhearing vehicle G's retransmission, which would result in that vehicle I also retransmits the packet and creates a parallel routing path towards the final destination. On the other hand, the design of TOPOCBF helps reducing packet duplicates at road intersections. In the previous example, the transmission of a routing packet from vehicle S needs to specify the next target intersection. If such intersection is Int1, vehicle I would discard the packet upon detecting that it does not provide a progress towards the targeted anchor point, and only vehicle G would retransmit it.

3.3. eTOPOCBF variant for improved channel efficiency

The previous section has shown the capabilities of TOPOCBF to control and limit the redundant overhead that may be generated by the broadcast nature of contention-based forwarding schemes. However, packet duplicates at intersections cannot be completely avoided with TOPOCBF. Referring to the scenario illustrated in Fig. 5, let us consider the case in which a packet, with Int1 as the next target intersection, is originated by node S and received by vehicles A, H, B and G, but not by vehicle C. Being the closest node to the center of Int1, vehicle B retransmits the packet first after selecting Int2 as the new target intersection. Let us now suppose that B's retransmission is overheard by vehicle E and all the vehicles placed in the road segment towards S, except vehicle A. The packet reception at vehicle E ensures that the packet is forwarded towards the final destination D, whereas the reception at vehicles placed along the road segment delimited by Int0 and Int1 ensures that their retransmission attempt is aborted. However, since vehicle A does not overhear the retransmission, a packet addressed to intersection Int1 is duplicated. This packet duplicate is discarded on every node that has already received the same packet addressed to Int1. However, the packet is not discarded by vehicle C since it only received the packet from vehicle B, which modified the *next intersection field* to Int2. Consequently, vehicle C has to forward the packet received from vehicle A, and a parallel forwarding path can be created if vehicle C does not select the same target intersection as vehicle B (i.e. Int2).

The situation previously described could be more frequent in high traffic density scenarios where vehicles are separated by very short distances and often concentrate at intersections. In such conditions, radio communications are further impaired by packet collisions that increase packet losses, and the probability of TOPOCBF generating redundant packet duplications at intersections and parallel forwarding paths increases as well. To cope with this problem, eTOPOCBF (efficient TOPOCBF) selects the next target intersection as TOPOCBF, but introduces two next *intersection fields* in the routing packets, and changes the policy to discard packet duplicates. The first *next intersection field* carries the position of the currently targeted intersection, while the second one includes the position of the previously targeted intersection. For every received packet in eTOPOCBF, vehicles keep track of the packet ID as well as the positions of the current and the previous targeted intersections. Packet duplicates are only discarded by a node if it previously received a packet with the same ID, and at least one of the two next *intersection fields* carried in the packet. To better understand this mechanism, let us reconsider the previous example depicted in Fig. 5 where vehicle C receives a packet retransmission from vehicle B. With eTOPOCBF, vehicle C will store for this packet its next target intersection (Int2) and its previous one (Int1). Later on, when vehicle C receives from vehicle A the packet duplicate with Int1 as the next target intersection, it discards it as it detects that Int1 was a previously targeted intersection. Consequently, vehicle C will not further retransmit the packet at Int1, which prevents the possibility to generate a parallel forwarding path.

4. Evaluation environment

4.1. The iTETRIS simulation platform

The performance of TOPOCBF has been investigated using the iTETRIS (Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions) simulation platform (http://www.ict-itetris.eu/10-10-10-community/) iTETRIS is an open source platform combining vehicular mobility and wireless communications simulation capabilities. It has been developed to allow for accurate and advanced large-scale studies of cooperative vehicular systems and applications. The iTETRIS platform is based on the architecture depicted in Fig. 7. The SUMO (http://sumo.sourceforge.net/) and ns-3 (http://www.nsnam.org/) blocks are devoted to model and simulate traffic mobility and wireless communications, respectively. The iCS (iTETRIS Control System) is a middleware module coordinating and synchronizing all the functional blocks involved in the simulation process. The Applications module is language-agnostic, and is implemented externally to facilitate the development and implementation

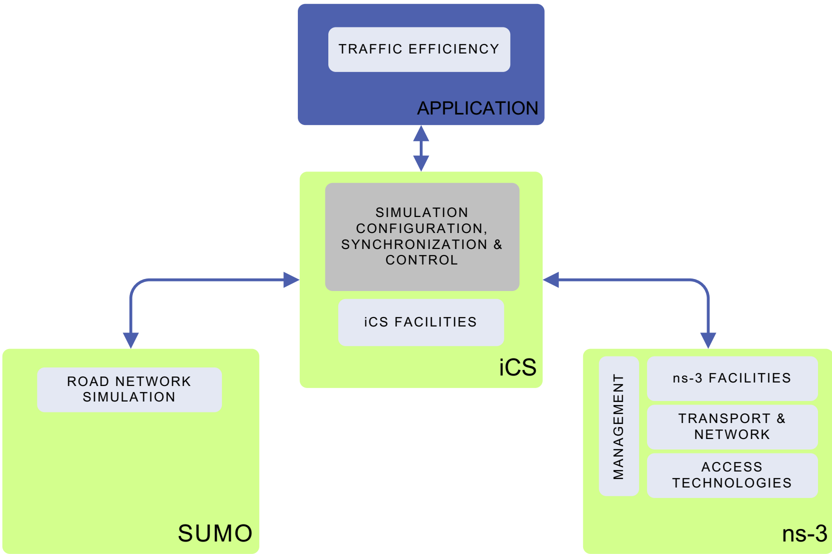

Fig. 7. iTETRIS's architecture.

of cooperative applications and traffic management strategies. This module will then interact with the rest of the platform with the assistance of the iCS. The interaction and exchange of information among the different simulation blocks is enabled through a set of interfaces based on IP sockets. The information is exchanged to and from the iCS following a client/server architecture, where the iCS is the client controlling and synchronizing the communication process, and the rest of blocks are servers that respond and act upon iCS requests. The iCS is therefore the entity that triggers the start of the different platforms, sets up the simulation environment, coordinates and controls the simulation execution. SUMO is controlled by the iCS to simulate vehicular mobility. It also keeps track of the vehicles' position, and provides them to the rest of the iTETRIS blocks through the iCS. ns-3 simulates the V2V and V2I wireless transmissions. The iCS, if requested by the simulated application, can schedule control messages to be sent to the ns-3 block in order to trigger the transmission of packets through the implemented radio access technologies. At the same time, ns-3 sends to the iCS information messages for every packet received whose content has to be processed by the application. Moreover, ns-3 is continuously fed by the iCS with the vehicles' position updates it retrieves from SUMO. Finally, the application may also react to the events generated and exchanged by the other iTETRIS blocks. For example, the reception of a given traffic speed indication at a vehicle might require to trigger a speed limitation action in SUMO.

The iTETRIS platform is compliant with the ETSI ITS Communications (ITSC) Architecture [24]. The implementation of the ETSI ITSC stack has been split between the iCS and ns-3 to reduce the computational load resulting from the continuous exchange of messages. ns-3 models the Access Technologies layer, and in particular implements the ETSI ITS G5A (the European adaptation of the IEEE 802.11p/WAVE standards), UMTS, WiMAX and DVB-H radio access technologies. The Transport & Network layer contains the necessary functionalities for packet addressing, routing and transport in vehicular scenarios over one of the communication stacks (GeoNetworking or TCP/IP) currently being defined by the work group 3 of the ETSI Technical Committee on ITS. The Management layer mostly implements functionalities for the dynamic selection of the most suitable radio access technology. The ns-3 iTETRIS module also includes the facilities functions specified in the European ITS communications architecture that are related to communications (e.g. message management, service management and addressing support), while the remaining facilities (e.g. relevance check, location referencing, station positioning, mobile station dynamics and LDM support) have been included in the iCS block for reducing the message exchange in the iTETRIS platform.

Different studies have demonstrated the importance of adequately modeling radio propagation effects to correctly design and evaluate cooperative vehicular communication protocols (e.g. [11]). To account for such effects, iTETRIS has integrated various propagation models for urban and highway scenarios modeling the pathloss, shadowing and multipath fading. For urban scenarios, iTETRIS includes the WINNER urban micro-cell propagation model for the 5 GHz band [25]. The propagation models are included in the ns-3 module implementing the ETSI ITS G5A access technology. This model differentiates between LOS (Line-of-Sight) and NLOS (Non-Line-of-Sight) propagation conditions. While the pathloss effect is modeled with a log-distance function, the shadowing effect is modeled with a log-normal distribution. The multipath fading effect has been modeled as a Ricean distribution for LOS conditions, and as a Rayleigh one for NLOS conditions. In addition to propagation losses, iTETRIS models the probabilistic nature resulting from radio transmission effects through the inclusion of the PER (Packet Error Rate) performance as a function of the Signal to Interference and Noise Ratio (SINR) [26]. Further details on the iTETRIS platform can be found in [27].

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4.2. GyTAR implementation

In order to highlight the efficiency to route packets by dynamically selecting multi-hop connected road segments independently from their vehicular density, TOPOCBF's performance is compared against that obtained by GyTAR [17]. To outline the dynamic routing mechanism used by GyTAR, let us consider the example depicted in Fig. 5. Every time a routing packet is received by a vehicle at intersection Int1 (e.g. vehicle B), GyTAR selects the next anchor point as the candidate intersection Int*i* that provides the highest score S_i according to the formula:

$$S_i = f(P_i) + g(D_i) \tag{3}$$

where $f(P_i)$ returns a value that is proportional to the progress P_i offered by Int*i* towards the destination D, and $g(D_i)$ is a non decreasing function of the vehicular density D_i offered by the road segment Int1-Int*i* and estimated through the IFTIS protocol [18]. Once the next targeted intersection has been selected, the vehicle transmits the packet towards it by adopting a sender-based greedy forwarding method similar to that specified in GPSR [9]; the scheme chooses as next forwarder the neighbor node that is closer to the next targeted intersection among those stored in the location table. In order to avoid that this choice always results in transmitting over the most unreliable links, two distinct GyTAR variants are tested in this work.[7] In the first one, referred to as "GyTAR a", a vehicle removes a neighbor from its location table if none of its beacon are received for a period of 1.5 s. In the second variant ("GyTAR b"), a neighbor is stored in the location table for 5 s, but the next forwarder is selected among the neighbors ensuring at least 2 beacon receptions in the last 4 s, and with the last beacon reception not older than 1 s.[8] It is finally important to point out that since this work is aimed at evaluating the capability of the protocols to route packets exploiting multi-hop connected road segments detected in real-time, the store-carry-and-forward recovery mechanism used by GyTAR in case of local maxima is not considered. For the same reason, and to fairly compare GyTAR to TOPOCBF, it is also assumed that in case a vehicle receives a routing packet at an intersection and it does not hold any IFTIS estimation of the vehicular density of adjacent road segments, the packet gets dropped.

4.3. Simulation scenario

The simulated routing packets fully comply with the format defined by ETSI for geonetworking transmissions [3]. Based on this format, the TOPOCBF and GyTAR schemes add 8 bytes to represent in the routing packets the position of the next intersection to target: 4 bytes to code the latitude, and 4 bytes to represent the longitude of each intersection. DiRCoD's implementation also codes the *CF* parameter with 1 byte, while the *CDP* packets used by IFTIS are implemented as geonetworking packets extended to carry the information about the vehicular density of each cell the roads are divided into. For the *CDP*'s payload portion dedicated to one IFTIS cell, 8 bytes have been considered to code the coordinates of the cell center and 1 byte to represent the cell density.[9] In addition, the *CDP* payload also includes some data of fixed size to represent the road segment identifier and the packet generation timestamp. This work assumes the use of 8 bytes to represent the road identifier, and 4 bytes to indicate the *CDP* generation timestamp. Eight additional bytes are added to indicate the geographical coordinates of the intersection to be targeted by the *CDP* packet after traversing all the cells of a road segment.

Without any loss of generality, the conducted simulations aim at reproducing the routing of a geounicast notification message between an originating vehicle and a fixed node in a Manhattan-like road network.[10] The geounicast transmission emulates a notification addressed to a distant area where vehicles could benefit from the reception of the notification (e.g. to modify their route in case of congestion); in this case, the fixed destination node represents the center of that area. Notification messages have a fixed application payload of 300 bytes, and are issued at a rate of 1 Hz. In addition, every simulated vehicle generates beacon messages with a 2 Hz frequency. Vehicles communicate using the 5.9 GHz ETSI ITS G5A radio interface, and transmit at a 6 Mbit/s data rate. Different transmission powers (14, 17, 20 and 23 dBm) are considered in order to investigate their impact on the protocols' performance and operation.

The adopted Manhattan-like road network (Fig. 8) consists of road segments with different lengths, number of lanes and traffic densities. In particular, the shaded roads in Fig. 8 represent streets with 3 lanes (2 in one direction, and 1 in the other), while the rest of the streets only have 2 lanes in total. Road intersections are not regulated by traffic lights except the intersection between the two 3-lanes roads, which experience higher vehicular densities. Realistic traffic mobility is simulated using SUMO, with the maximum speed being limited to 50 km/h. Four different traffic scenarios have been simulated. Vehicular densities are characterized through the Level of Service (LOS) metric proposed by the HCM manual [28]. This metric represents a quality measure to describe the operational conditions within a traffic stream by analyzing the average driving speed and vehicular density. Six different levels of service are defined, with LOS A representing free-flow conditions and LOS F describing severe congestion situations. For city scenarios, the Skycomp Company categorizes the LOS metric based on the number of vehicles in observed platoons [29]. The first simulated scenario (Scenario 1) is characterized by an

[7] It is important to note that these two variants were not presented in the original GyTAR proposal [17]. The variants are here proposed after evaluating GyTAR under realistic propagation conditions, and noticing its poor performance resulting from the selection of unreliable multi-hop links. The performance obtained under realistic propagation conditions by the original GyTAR implementation was significantly lower than that reported in this paper through the two proposed GyTAR variants.

[8] This mechanism is the same as used by DiRCoD to estimate the reliability of a neighbor.

[9] It has been considered that 8 bits are enough to represent high density scenarios consisting of up to 255 vehicles per IFTIS cell.

[10] In this paper, a Manhattan-like road network is adopted to ease the implementation of the protocols. The operation and performance of DiRCoD and TOPOCBF are expected to be maintained in other types of road networks as long as they can be represented as sets of road segments divided by anchor points.

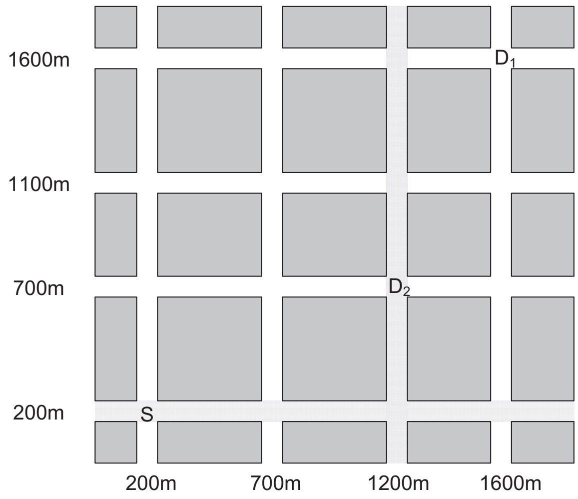

Fig. 8. Urban Manhattan-like scenario.

average vehicular density of 6 vehicles/km/lane for all the streets. This traffic density results in a LOS A (“very light traffic”) since almost no queues are present at road intersections. Scenario 2 is characterized by a vehicular density of 10 vehicles/km/lane over the streets having 3 lanes. This density results in platoons of less than 15 vehicles corresponding to a LOS C (“moderate traffic”) for the streets with 3 lanes, while the other streets still experiences LOS A. The third scenario (Scenario 3) has a vehicular density of 10 vehicles/km/lane for the streets with 3 lanes (LOS C), and of 8 vehicles/km/lane in the other streets. This density results in queues of a few vehicles at intersections, which corresponds to LOS B (“light traffic”) according the Skycomp’s definitions. Finally, Scenario 4 corresponds to an average vehicular density of 10 vehicles/km/lane in all the streets, reproducing a uniform LOS C level over the complete road network.[11] It is important to highlight that the higher the number of the scenario, the higher the vehicular density over the whole Manhattan-like road network. In fact, while scenario 1 corresponds to an overall vehicle traffic density of about 6 vehicles/km/lane, scenarios 2, 3 and 4 model vehicular traffic densities of approximately 7.2, 8.6, and 10 vehicles/km/lane, respectively. For all the scenarios, the positions of the geounicast packets’ source (S) and destination (D_1 and D_2) have been fixed as shown in Fig. 8. This will allow better comparing how routing protocols are influenced by the spatial distribution and the density of the vehicular traffic.

The results reported in the following sections have been obtained through simulations with an accuracy equivalent to relative errors below 0.05.

5. Performance evaluation

The performance of the routing protocols is first evaluated as a function of the vehicular traffic conditions. The transmission power has been set to 23 dBm (200 mW), which results in a communications range of 115 m. The destination node has been set to D_1 in Fig. 8. A preliminary simulation-based optimization analysis has been conducted to identify the values of the parameters that maximize the performance of the compared routing schemes. For the case of TOPOCBF, it has been verified that using a DiRCoD’s *CF generation period* of 2 s is enough to provide TOPOCBF with up-to-date road connectivity information. Using lower values increases DiRCoD’s communications overhead without improving TOPOCBF’s packet delivery performance. The conducted analysis has also shown that setting DiRCoD’s intersection zones to a relatively large radius *R* (30 m) is beneficial as it gives passing vehicles more time to receive at least one road connectivity assessment before leaving the intersection. Setting the *connectivity expiry time CET* to 6.5 s (three times greater than *CF generation period*) also improves TOPOCBF’s packet delivery performance since it allows vehicles to forward packets at intersections even if DiRCoD’s road connectivity estimates could not be updated very recently. Using higher *CET* values did not improve TOPOCBF’s performance, but increased its communications overhead.

Fig. 9 compares the Packet Delivery Ratios (PDR) achieved under the four simulated traffic scenarios. TOPOCBF schemes exploit DiRCoD’s connectivity estimates to forward packets over subsequent multi-hop connected roads. The TOPOCBF schemes achieve higher PDR due to DiRCoD’s capability to continuously provide vehicles at intersections with up-to-date road connectivity information, and due to the increased reliability of the adopted broadcast forwarding scheme. Since TOPOCBF can duplicate packets at intersections, it can create parallel forwarding paths that increase the possibilities to reach the final destination and result in a slightly higher PDR compared to eTOPOCBF. This difference disappears under dense traffic scenarios (Scenario 4) where all road segments tend to be multi-hop connected. The lower GyTAR PDR performance is caused by IFTIS’s inability to adequately inform vehicles crossing intersections about the traffic density of the adjacent road segments, and by the unreliability of the adopted sender-based forwarding scheme under large and rapid signal level variations characteristic of wireless environments. Even if more robust schemes are used to select the next forwarder (GyTAR b), GyTAR’s performance is still significantly lower than TOPOCBF. A more in depth analysis shows that GyTAR packet losses are due to different factors depending on the traffic scenario. In the scenario with lower vehicular density (Scenario 1), packets losses are mostly due to the lack of any IFTIS density information at intersections, or because the packet reaches a local maximum over a given road segment.[12] In particular, these two factors explain 92% of GyTAR b’s packet losses. On the other hand, the majority of packet losses (70% for GyTAR b) is due to radio

[11] Please note that increasing scenarios’ numbering represents increasing values of the simulated vehicular traffic density in the overall Manhattan-like road network.

[12] Both effects are caused by the low vehicular density. In this context, *CDP* packets are not frequently received at intersections, and vehicles that have to route a packet at an intersection either do not hold any vehicular density information about the adjacent road segments (and thus drop the packet), or hold outdated information that may not represent the current roads’ density (and forward the packet towards local maxima).

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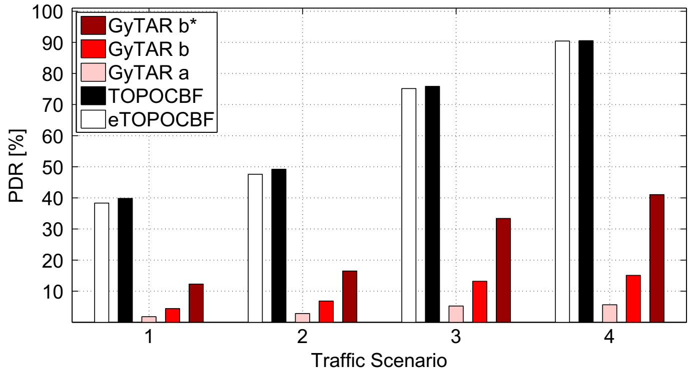

Fig. 9. Packet delivery ratio for the four simulated traffic scenarios.

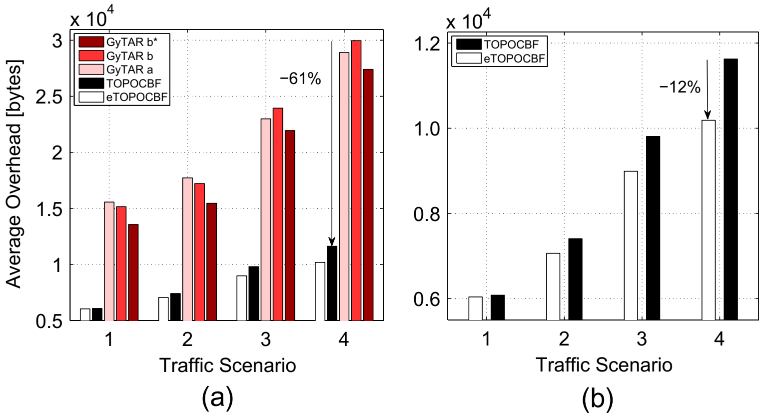

Fig. 10. Average routing overhead for the four simulated traffic scenarios.

transmission errors under higher vehicular densities (Scenario 4). To understand why GyTAR exhibits a significantly different performance in this study compared to [17], GyTAR has also been evaluated using simulation settings trying to approximate those indicated in [17]. To this aim, a simplistic Two-Ray Ground Reflection propagation model and a 3 dBm transmission power are used. Following the definition of communications range adopted in this study, these settings result in a 255 m communications range. As expected, a simplified propagation modeling increases GyTAR robustness ("GyTAR b*" in Fig. 9) and improves its PDR under all the traffic scenarios. However, the identified inefficiencies still result in a lower PDR performance compared to TOPOCBF.

Fig. 10 compares the protocols' communications overhead (in bytes). The overhead is computed considering all the packets transmitted to correctly route messages towards the final destination. In addition to the routing packets, TOPOCBF's overhead also includes the overhead generated by DiRCoD's *CFs*. Similarly, GyTAR's overhead includes IFTIS' *CDP* transmissions. The average overhead reported in Fig. 10 is then obtained by dividing the overall measured overhead by the number of routing packets generated by the source node. The results depicted in Fig. 10a show that even if GyTAR is able to only deliver a small percentage of packets to the destination, it always generates a larger average overhead compared to the TOPOCBF schemes. This is mostly due to the significant amount of communications overhead generated by IFTIS (on average, it represents 73% of the total GyTAR's overhead), and to the many packet retransmissions resulting from packet failures at link level.[13] On the other hand, TOPOCBF schemes rely on broadcast transmissions and hence do not imply such retransmissions. Moreover, they require a relatively low amount of communications overhead for road connectivity computation; in fact, DiRCoD only generates on average around 14% of the total TOPOCBF's overhead. This results in that TOPOCBF generates up to 61% less average overhead than GyTAR b in Scenario 4. As previously explained, eTOPOCBF was designed to prevent packet duplications at intersections. This results in that eTOPOCBF reduces the average overhead by up to 12% compared to TOPOCBF (Fig. 10b). The results reported in Fig. 9 show that this overhead gain is obtained without compromising its PDR.

In addition to reducing the communications overhead, Section 3 indicated that estimating road connectivity rather than traffic density could help distributing the communications load over the road network, and avoid

[13] Please note that the simplistic propagation model considered for GyTAR b* reduces the number of retransmissions and, consequently, also the communications overhead compared to evaluating GyTAR under more realistic propagation environments (−9% over all the traffic scenarios).

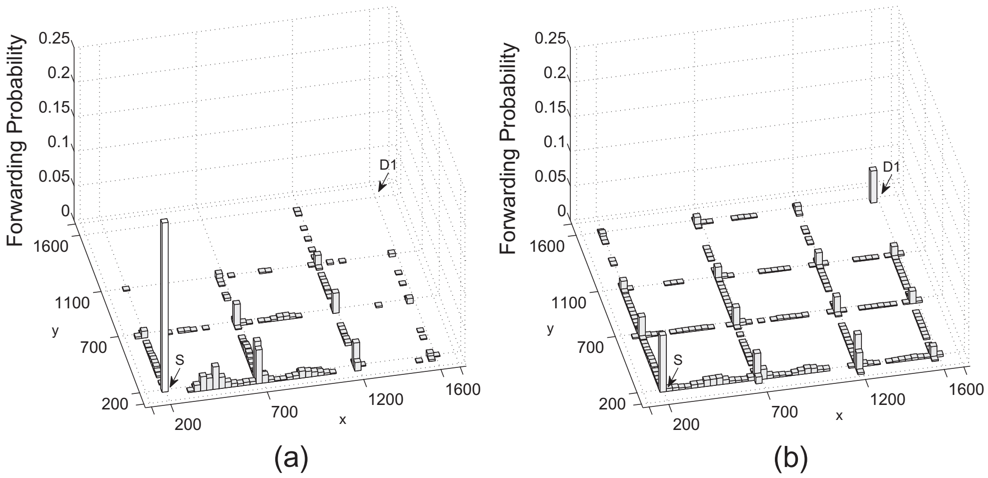

Fig. 11. Spatial distribution of the packet forwarding probability for GyTAR b (a) and TOPOCBF (b) (traffic scenario 2).

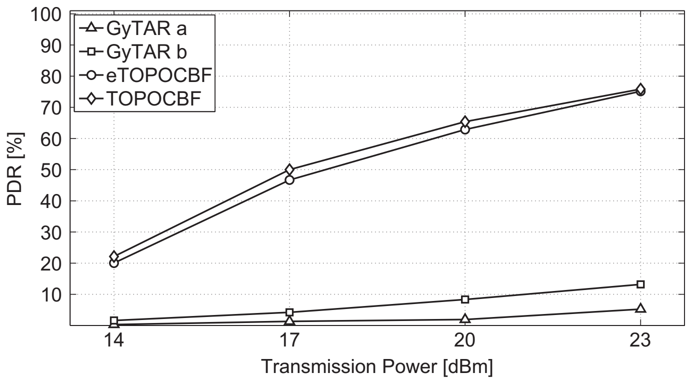

Fig. 12. Packet delivery ratio as a function of the transmission power.

congesting the communications channel in areas with higher road traffic densities. To analyze this effect, Fig. 11 represents the spatial distribution of the packet forwarding probability over the simulated road network.[14] The results illustrated in Fig. 11 correspond to the traffic Scenario 2 in which the 3-lanes road from point (200,200) to point (1600,200) experiences a much higher traffic density than the 2-lanes road from point (200,200) to point (200,1600). The results depicted in Fig. 11a show that GyTAR mostly selects the intersection at (700,200) as next anchor point when a packet is generated at the source node. In addition, GyTAR tends to retransmit the packets over the most dense road segments. On the other hand, TOPOCBF distributes more evenly over all the road segments the forwarded packets (Fig. 11b). This results from the fact that DiRCoD's connectivity does not represent a direct estimation of vehicular traffic density, and thereby TOPOCBF can route packets over road segments that do not experience the highest densities. This capability allows TOPOCBF to reduce the communications load over the road segments that are more prone to suffer channel congestion. This important benefit is achieved without reducing the PDR performance.

The previous results were obtained for a 23 dBm transmission power. Fig. 12 shows for traffic Scenario 3 (the same trend has been observed for the other traffic scenarios) that increasing the transmission power augments the PDR as a result of a higher communications range and a higher probability to find forwarders for multi-hop transmissions. The obtained results also show a similar performance comparison trend between TOPOCBF and GyTAR irrespectively of the transmission power. In terms of routing overhead, Fig. 13 confirms the lower overhead of TOPOCBF schemes compared to GyTAR irrespectively of the transmission power. In fact, TOPOCBF reduces the average overhead by more than 57% compared to GyTAR b (Fig. 13a); eTOPOCBF further reduces the average overhead by up to 9% compared to TOPOCBF (Fig. 13b). It is important to note that, by decreasing the transmission power, packets are transmitted over more hops of shorter length, but only a reduced percentage of them successfully reaches

[14] This probability is computed by dividing the road network in square cells of 30 m $*$ 30 m. Each bar considers the packet forwarding events that have taken place at each square cell.

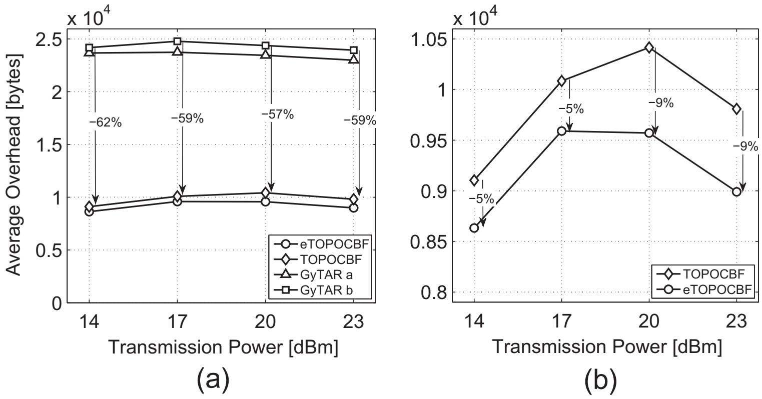

Fig. 13. Average routing overhead as a function of the transmission power.

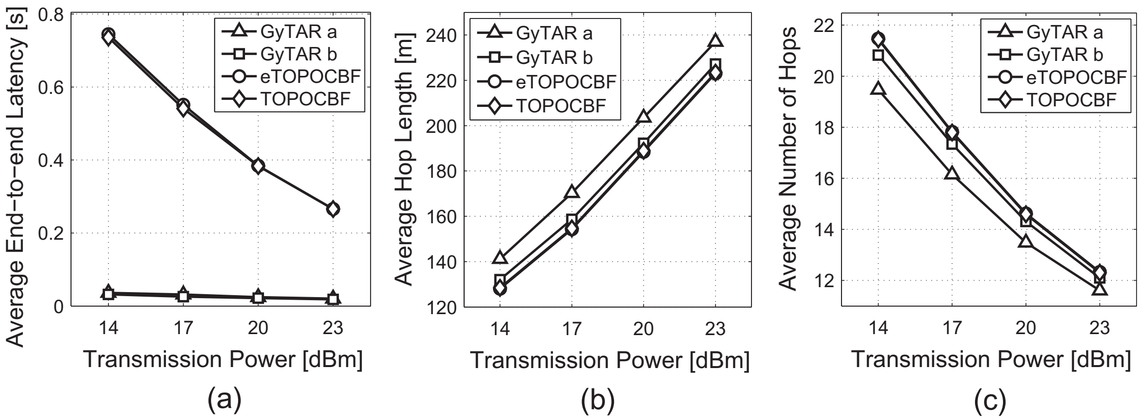

Fig. 14. Average end-to-end latency (a), hop length (b), and number of hops (c) as a function of the transmission power.

the destination. This results in that the amount of communications overhead generated by transmitting with lower transmission powers almost equals the overhead produced with higher powers, where less hops are needed, but more packets are correctly forwarded towards the destination (Fig. 13a).

The previous results have demonstrated the significant PDR and overhead benefits of TOPOCBF schemes exploiting DiRCoD's multi-hop connectivity information. These benefits are in part due to TOPOCBF's contention-based forwarding approach as opposed to GyTAR sender-based forwarding. As shown throughout this study, contention-based forwarding adds robustness in the selection of next forwarders. However, this robustness is added at the expense of increasing the end-to-end latency needed to deliver a routing packet from source to destination (Fig. 14a). This is due to the fact that while GyTAR retransmits packets as soon as the next forwarder is chosen, TOPOCBF adds at each hop a *forwarding timeout* based on (1), and ranging from 0 to t_{max} (here set to 0.1 s) depending on the progress provided towards the next targeted intersection. The results depicted in Fig. 14a show that TOPOCBF's end-to-end latency can be significantly reduced as the transmission power augments. By increasing the transmission power, nodes are able to communicate with more distant vehicles, thereby increasing the average hop length (Fig. 14b) and decreasing the number of hops (Fig. 14c) used in the packet forwarding process. As a result, TOPOCBF schemes can considerably reduce their end-to-end latency, passing from 0.75 s using a transmission power of 14 dBm to 0.26 s using 23 dBm. Fig. 14b shows that GyTAR's sender-based forwarding scheme always results in longer hops compared to TOPOCBF, which reduces the end-to-end latency (Fig. 14a). However, longer hops between GyTAR forwarders also reduce the links' reliability, and significantly degrade the packet delivery ratios (Fig. 12).

GyTAR's PDR degradation resulting from the unreliable selection of forwarders can increase not only with longer hops, but also when the number of hops between source and destination increases. To analyze this effect, Table 1 compares the GyTAR and TOPOCBF performance when shortening the distance between source and destination nodes under traffic Scenario 3 and a 23 dBm transmission power. In particular, the performance obtained with the original destination at D_1 (referred to as "Long" in Table 1) is compared to that obtained when placing the destination node at D_2 ("Short" in Table 1) in the road network illustrated in Fig. 8. Reducing the distance between source

Table 1
TOPOCBF and GyTAR performance for different distances between source and destination.

	Packet delivery ratio (%)		Average overhead (bytes $*10^4$)		Average end-to-end delay (ms)		Average number of hops		Average hop length (m)	
	Long	Short	Long	Short	Long	Short	Long	Short	Long	Short
GyTAR a	5.23	20.82	2.30	2.17	20.23	8.90	10.83	5.76	237.00	257.81
GyTAR b	13.18	31.79	2.39	2.23	18.20	8.40	11.54	5.87	227.19	252.76
TOPOCBF	75.86	91.54	0.98	0.60	265.55	109.50	11.88	6.19	223.43	239.54
eTOPOCBF	75.15	91.35	0.90	0.53	265.86	109.79	11.84	6.17	223.06	239.08

and destination nodes decreases the average number of hops necessary to reach the destination to almost 6 hops. As a result, the probability to drop packets due to radio transmission errors decreases for GyTAR schemes, which significantly augments their PDR. However, the same benefit is observed for the TOPOCBF schemes that reach PDR values exceeding 90%. Reducing the distance between source and destination decreases more significantly the routing overhead for TOPOCBF than GyTAR. This is due to the fact that most of GyTAR's overhead is due to IFTIS transmissions for estimating the road density. Since the number of IFTIS messages does not vary as the position of the destination is changed, the impact of the distance between source and destination is not very significant for GyTAR schemes. On the other hand, most of TOPOCBF's routing overhead is not due to DiRCoD's connectivity estimates but to the transmission of routing packets between source and destination. As a result, shorter distances significantly reduce TOPOCBF's average overhead.

6. Conclusions

This paper has presented and evaluated TOPOCBF, a new contention-based forwarding protocol that dynamically selects its routing paths based on their multi-hop connectivity estimated using the DiRCoD technique. The proposed protocol is aimed at reducing the communications overhead characteristic of routing protocols using vehicular traffic density estimates, and at avoiding the potential unreliable selection of relay nodes resulting from sender-based forwarding. The performance and operation of TOPOCBF has been analyzed for different traffic scenarios, transmission power levels, and distance between source and destination. In addition, its performance has been compared to that obtained with the GyTAR technique. The obtained results demonstrate TOPOCBF's capability to provide high packet delivery ratios while reducing the communications overhead and spatially distributing the communications load over the road network. These benefits are obtained at the expense of a slight increase of the end-to-end delivery latency, although the experienced latency levels are quite low considering the distances between source and destination. In addition, TOPOCBF end-to-end latency levels can be considered acceptable for the majority of cooperative ITS applications requiring multi-hop communications.

TOPOCBF has been shown to be able to reliably and efficiently forward information to geo-referenced destinations. Future research efforts should then be devoted to dissemination schemes that coupled with TOPOCBF could efficiently distribute the information around the target destinations. Moreover, it would be of interest to investigate the possibility to further improve the performance of routing and dissemination schemes with store, carry and forward capabilities.

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