INTERNATIONAL JOURNAL OF SATELLITE COMMUNICATIONS AND NETWORKING

Int. J. Satell. Commun. Network. 2016; **00**:1–34

Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/sat

RLNC in Satellite Networks:
A Cooperative Scenario for Delivering M2M Traffic

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SUMMARY

The fraction of Machine-to-Machine (M2M) traffic carried by satellite networks is increasing, and an efficient delivery is required, in order to enable a large set of applications that can benefit from the advantages provided by the use of satellites. This work analyses the use of Random Linear Network Coding (RLNC) techniques in Land Mobile Satellite (LMS) channels to reliably deliver M2M traffic to mobile nodes in urban areas. The considered scenario takes into account a cooperative coverage extension in LMS vehicular networks, where the use of RLNC techniques can remove the need for any fixed equipment on the ground at least in urban environments, where the density of mobile nodes is typically high. Copyright © 2016 John Wiley & Sons, Ltd.

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KEY WORDS: Network Coding, Satellite, VANET, M2M, gossiping

1. INTRODUCTION

The application of Network Coding (NC) to communications networks is relatively recent and dates back to year 2000 [1]. Since then, NC has shown great potentials in correcting random packet errors, erasures, and errors introduced by malicious nodes, making it a powerful tool to achieve efficient

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network service delivery and network reliability. In the seminal work by Ahlswede et al. [2], NC is illustrated in the butterfly network example: a data source delivers a stream of messages to two receivers; all links can deliver up a single message per unit of time. In the example, the middle link represents a bottleneck and, to overcome that, the authors propose to send a combination of the messages instead of plain packets. Two incoming messages a_i and b_i are XORed, $a_i \oplus b_i$, then the coded packet $a_i \oplus b_i$ is sent in the middle link, reaching the two receivers in a single unit of time. The two receivers can reconstruct the whole piece of information by XORing the network coded packet and a_i (or b_i), which comes on a separate link. In this way, the throughput of the network is increased, because less packet transmissions are needed to deliver the whole information block. Linear NC (LNC) is introduced by Li et al. in [3, 4]: the idea behind LNC is to create combinations of packets by taking coefficients from a Galois Field of size $q = 2^x$. The original messages can be retrieved, at destination, by performing Gaussian elimination on the matrix generated from the LNC coefficients of the packets. Considering k source packets, a so-called *generation* worth of k input symbols, $n \geq k$ output symbols are generated by the coding procedure. If at least k independent symbols are received at destination, then decoding is possible. RLNC has been proposed in [5, 6] in 2003: when employing RLNC, the coefficients are randomly drawn from the finite field. According to [5], the failure probability when relying on RLNC depends on the size q of the finite field. The larger q, the lower the failure probability, but at the price of a larger packet overhead and larger lookup tables[†] to be maintained in memory [7]. Anyway, it should be noted that a larger q provides a lower energy per bit cost [7], thus an interesting future direction sees the use of iterative algorithms instead of large lookup tables.

There are tens of possible application of NC in communication networks, to achieve the most various objectives; for instance: an increase in the achievable throughput, robustness to packet losses, robustness to link failures, reduction of complexity in routing strategies, and security purposes. In [2], NC is used to increase the achievable throughput: thanks to the multiple paths

[†]Typically, a Galois Field is implemented as a lookup table, which allows to perform field operations by reading from a low-cost memory.

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DOI: 10.1002/sat

connecting the source and the destinations, less transmissions of packet combinations are needed to fully transmit the original data compared to the case without the use of NC techniques. In [2], a multicast scenario is considered, but the use of NC shows advantages also in unicast scenarios, and wireless connectivity is used. Wireless connections are typically more affected by packet losses than wired connections, and the use of NC can counteract losses by introducing coding along the path. Classical erasure coding helps in protecting against losses at the cost of delay, which can be large if erasure coding is applied hop-by-hop to protect against variable loss rates. By using NC techniques, hop-by-hop coding is available and provides a lot of advantages w.r.t. the use of erasure codes: such technique is referred to as *recoding* at intermediate nodes. RLNC is particularly suited in scenarios affected by different loss rates on the links composing the whole path [5, 6]. Losses can also come from link failures. In the absence of NC techniques, routing schemes are required to re-route the information in order to exclude broken links; instead, the use of NC allows a faster recovering and re-routing is not needed, because the use of NC techniques over multiple links can ensure live-path protection from non-ergodic link failures [6]. Last but not least, NC provides a reduction of the complexity when considering multicast routing scenarios. A multicast scenario without the use of NC techniques may require the construction of complex routing strategies; instead, when using NC techniques, a linear optimization is possible, based on the use of low-complexity distributed solutions [8, 9], where NC can be seen as a superset of routing. Finally, NC can be used to secure communications [10, 11]: NC packets cannot be decoded if the attacker is not able to collect enough information, for instance if a single node is under malicious control. On the other side, an attacker can replace coded packets with malicious contents and this is more difficult to detect than plain attacks.

This work considers a scenario where M2M data are sent in a multicast fashion from a single remote source via satellite to multiple receivers. For instance, software upgrades distributed over-the-air, traffic updates, weather forecasts, local maps, and so on, are relevant use cases of traffic

DOI: 10.1002/sat

distributed to *connected cars*[‡] in the considered scenario. Here, we take into account two different phenomena that can affect the reliability of the transmission: packet losses because of fading and because of the presence of obstacles, and the presence of intermittent links in the terrestrial segment, due to the fact that the nodes move, originating a fast-changing network topology. The purpose of the VANET is to increase the probability that each node can successfully decode the data coming from the satellite, exploiting a cooperative diffusion strategy, also known as *gossiping* [12]. The concept of gossiping is largely used in the literature to describe probabilistic algorithms for data forwarding in dissemination scenarios: it means that each node in the network participates in the diffusion of the information, aiming at increase the probability that all nodes correctly receive it. The multicast scenario under consideration is a typical use case in satellite scenarios. Yet, the main aim of this work is using NC techniques to ensure the largest possible coverage, and removing the need for any fixed ground equipment.

Generally speaking, Internet Protocol (IP) multicasting is a key networking technique for reaching a large number of users with a single transmit operation. The most notable application of this technique is the use of satellites for distributing audio/video contents due to the inherent broadcast nature of satellites and their large area coverage. If relying on the Digital Video Broadcasting - Satellite Services to Handhelds (DVB-SH) [13] standard - the satellite version of Digital Video Broadcasting - Handheld (DVB-H) [14] - several vehicular applications can also benefit from satellite networks in order to reach a wide set of customers. As far as vehicular applications are concerned, satellite transmission can be impaired by a number of factors in cities, such as the presence of buildings and other obstacles. To overcome the latter issue, the use of terrestrial gap-fillers has been proposed in [13], where they are referred to as Complementary Ground Component (CGC). The gap-fillers act as repeaters, extending the satellite coverage in areas where

[‡]The concept of connected cars is actively investigated by the European Commission, among others; more specifically, the *Directorate-General for Mobility and Transport* is directly involved in several research and deployment actions on this topic. Furthermore, car vendors are convinced that OTA software updates for quality management, recall management, or sending features or notices, can be done over a majority of countries through satellite-based communications.

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the satellite signal strongly degrades because of the obstacles. It is very likely that, in the very near future, the upcoming Intelligent Transportation Systems (ITS) paradigm, together with a plethora of innovative services for customers, will foster using Road Side Units (RSUs) alternatively to CGCs, to allow short range communication in Vehicular Ad-Hoc Networks (VANETs). In fact, RSUs may represent the ideal complement to existing communication infrastructures, in order to provide high mobility support in large networks. The paradigm Vehicle-to-everything (V2X) arises here, and IEEE 802.11p [15] is the de facto standard for terrestrial wireless communications. Wireless Access in Vehicular Environments (WAVE) is an approved amendment to the IEEE 802.11 standard to support ITS applications, and its specifications support data exchanges between moving vehicles, and between vehicles and fixed equipment, like RSUs. In V2X scenarios, the satellite component may play a role as complementary network, in order to ensure the desired coverage in urban, suburban, and rural areas.

2. RELATED WORKS

Reliable multicast via satellite has been thoroughly analysed in the literature in the last years. A valuable survey is provided in [16], underlining how satellites offer a natural way to reach a large number of users, bypassing the issues that terrestrial networks may pose, such as the traversing of several terrestrial networks, which can be potentially congested; on the other hand, the use of satellites, usually geosynchronous (GEO) ones, can pose other issues: for instance, scalability, when several thousands of receivers produced by different manufacturers are contemporarily served by a GEO satellite in a multicast scenario [16]. Reliability can be an issue, too, in presence of a vast population of terminals listening to multicast transmissions, because different groups can experience different loss rates and, in the absence of a feedback channel, it is impossible for the sender to determine if data has been correctly received by all the receivers. In the latter case, Forward Error Correction (FEC) techniques, applied at physical layer or as packet level FEC, are typically used to reduce the error rate.

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In [17], the use of NC techniques in satellite scenarios is analysed when GEO and low earth orbit (LEO) satellites are employed: the scenario under consideration takes into account the presence of terrestrial repeaters, focusing on the next generations of satellite networks, which offer more features than just regular bent-pipe systems. NC support within On-Board Processing (OBP) is a promising technique, as alternative to FEC mechanisms [17]. A similar multicast scenario is described in [18], in cases of fixed and mobile terminals, where NC is proposed as part of the encapsulation protocol of the satellite stack, in order to provide transparency towards the upper layer protocols. The proposed communication architecture exploits a feedback channel in order to guarantee a reliable data transfer; anyway, the so-called *feedback implosion* can be a major issue [19] when feedback channels are employed in multicast scenarios.

In [20], the case of multiple sources transmitting data via a satellite link to a single receiver is analysed. The sources exchanges packets prior to transmission, and these packets are coded together by relying on RLNC techniques. The different sources are spaced apart, thus introducing spatial diversity when transmitting on the satellite channel. The different geographical positions helps in reducing the system outage probability, even in deep fading conditions, as produced by the randomness of the surrounding environment. The work in [20] shows that the use of RLNC techniques can be an effective strategy to counteract random losses in communication channels, but at the expense of the channel capacity: a trade-off is necessary, which should take into account bandwidth requirements and channel statistics. Furthermore, the assumption that different sources are sufficiently spaced apart to experience different fading conditions, while being inter-connected via terrestrial links, is an unlikely scenario in real installations.

The work in [21] considers a multicast scenario in urban areas. The mobile nodes, moving according to the Manhattan Grid (MG) mobility model [22], have a DVB-SH radio interface to receive data from satellite, and they cooperate in ensuring the possible largest coverage on the ground, exploiting IEEE 802.11p-based communications thanks to a vehicular radio interface. LMS communications are then in place, according to the channel models in [23, 24]. The main objective in [21] is to limit the number of needed gap-fillers, while still ensuring reliable data transfers,

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thanks to the mobile nodes acting as mobile gap-fillers (MGFs). This scenario is then deepened in [25], which takes into account the use of RLNC for cooperative coverage extension in LMS vehicular networks: an analytical assessment of the advantages that gossiping grants is provided, in the presence of CGC. A minimum number of gap-fillers is necessary, according to the authors, in order to maintain a low outage probability and to extend the coverage. In [25], NC is applied to Multi Protocol Encapsulation - Inter-burst Forward Error Correction (MPE-IFEC) [26] symbols. The outcomes of [25] show that there is a trade-off between the coverage and the rate at which the information can be injected into the network, and that the larger is the number of mobile nodes, then the larger is the gain provided by such a cooperative approach.

3. MAIN CONTRIBUTIONS OF THIS WORK

This work considers a scenario similar to that proposed in [21, 25], aiming at limiting the number of CGC/RSU equipment on the ground, thanks to a RLNC-based cooperative approach. In this paper, we show that CGC/RSU equipment can be completely eliminated in urban areas, thanks to the specific characteristics of mobility in cities and to the use of RLNC techniques. The main contributions can be summarized as follows:

- we developed a simulator to assess the benefits that NC provides in the presence of reliable multicast transmissions via satellite towards a VANET in an urban area;
- we show how the need of any fixed ground equipment can be completely eliminated, while ensuring a large coverage probability on the ground;
- we propose an analytical framework to evaluate the joint effect of the vehicular cooperation and the application of RLNC techniques, with a focus on realistic mobility models and their impact on the numerical results.

In the following, the scenario under consideration is described in Section 4. The analytical model of the system is presented in Section 5, and the performance evaluation is carried out in Section 6,

DOI: 10.1002/sat

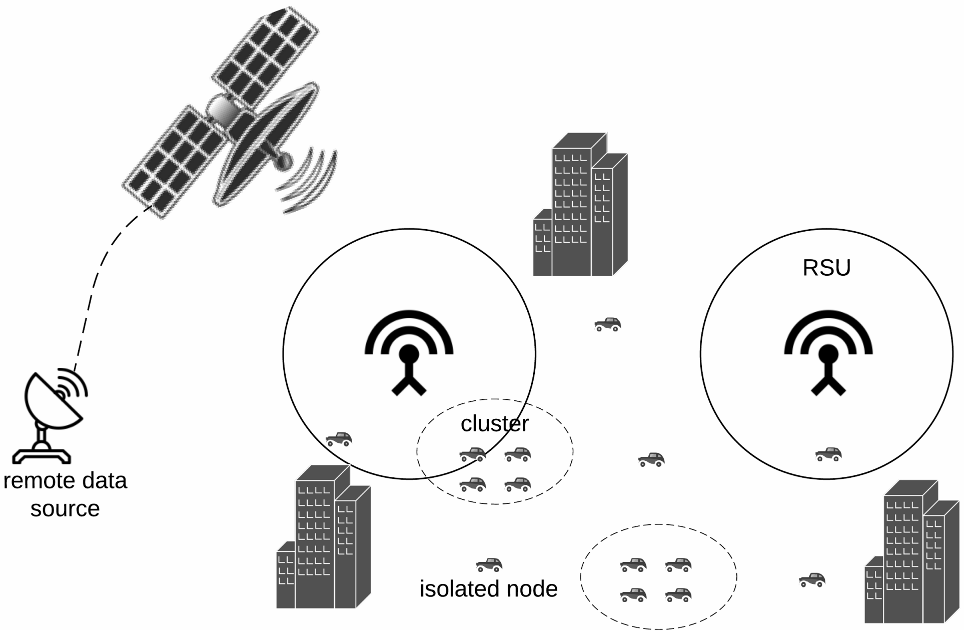

Figure 1. Logical description of the scenario under consideration

where we show the impact of different mobility models in gossiping scenarios, and the advantages that the use of RLNC techniques can provide. Eventually, the conclusions are drawn in Section 7.

4. SYSTEM MODEL

The application scenario shown in Figure 1 accounts for a remote service provider, which multicasts data for M2M applications via satellite towards connected cars in an urban area. On the ground, the presence of RSUs allows to extend the coverage in areas where the link quality is poor because of the presence of obstacles. The data source applies RLNC techniques to outgoing data packets, and coded packets are received by vehicular On-Board Unit (OBU) and RSUs, both equipped with two radio interfaces: DVB-SH and IEEE 802.11p. The latter is used to *gossip* the received M2M data to close neighbors.

The main objective of this work consists in understanding if RSUs/CGC are really needed to ensure full coverage or if the use of RLNC techniques may be sufficient to achieve, at least the same result, at the price of a larger gossiping probability p_g, which is defined as the probability to forward (gossip) any received data to the neighbors within the communication range. The *full*

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CGC	**RSUs**
transparent to OBUs	transparent to OBUs
large covered area (≈ 10 km^2)	reduced covered area (< 1 km^2)
DVB-SH radio	DVB-SH and 802.11p radio interface
few different stakeholders	large number of potential stakeholders

Table I. A brief comparison between CGC and RSUs.

coverage level is here defined as the probability P_{cov} that at least 99% of mobile nodes can correctly decode M2M data. We provide an analytical model in Section 5 that estimates the probability of correctly decoding data, when RLNC is in use, thus removing the need for RSUs. In order to further clarify the differences between CGC and RSUs in use in this work, we provide a brief comparison in Table I. RSUs have the same connectivity features of a mobile node and operate as fixed equipment on the ground. In the satellite domain, CGC is defined at physical level as a signal repeater: it complements the data reception in areas where the satellite coverage cannot be guaranteed. RSUs absolve to the same function, but the hardware and the architecture are general purpose: they operate as gateways between broadband networks and local terrestrial vehicular communications, by broadcasting messages received from the satellite to 802.11p radio adapters. Both RSUs and CGC are transparent to receivers. In a more general scenario, some vehicles may not be equipped with the satellite receiver, but they can still be acting as MGFs, because they receive data from fixed or mobile nodes within the communication range. The received data is gossiped, in order to extend the coverage on the ground. In our scenario, gossiping is limited to a single hop, in order to prevent uncontrolled flooding. A multi-hop scenario introduces further complications, for the following reasons: (*i*) multi-hop gossiping increases the risk of an uncontrolled data flooding, which should be prevented at any cost, in order for any gossiping strategy to be useful; (*ii*) some policies are needed in this case, for instance about information aging, or about priority for transmitting old or fresh data; (*iii*) out of order data must be handled, as far as different paths may experience different

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propagation delays; (*iv*) multi-hop is more costly from an energetic point of view, because a larger number of transmissions is expected, on average. A multi-hop gossiping strategy requires some sort of coordination, centralized or distributed, in order to avoid a too large collision rate in the network. On the other side, multi-hop gossiping increases the probability that all nodes receive all data: this can be useful if the density of the nodes reduces. We prove in Section 6 that single-hop gossiping is sufficient to guarantee a full coverage level for urban scenarios, where the density of nodes is typically moderate/high.

In the following, we discuss the impact of the mobility model on the effectiveness of a gossip-based protocol in Section 4.1, the assumptions related to the satellite channel in Section 4.2, and the assumptions related to the terrestrial link in Section 4.3.

4.1. Impact of the mobility models

The mobility pattern in cities has specific features that affect the effectiveness of a gossiping algorithm. In cities, *clusters* of vehicles are common: for instance, in presence of traffic jams or close to traffic lights. A mobility model based on real collected traces and able to capture, at the same time, sparse and clustered network partitions, can help in simulating a more realistic scenario than relying on typical mobility models, such as MG or Random Walk (RW) models, which are commonly used in the literature. If we consider the hypothesis of data distribution outside of urban areas, the lack of a high density of users should be taken into account, because it may reduce the interest in the use of gossiping techniques, as in this work. In such a case, the probability that some users cannot correctly receive all data increases; anyway, some countermeasures can be deployed, such as caching techniques. A mobile node stores what correctly received in a cache memory: when it meets other users, cached data can be exchanged, thus increasing the possibility of filling any data holes. Anyway, we do not consider the use of caching mechanisms in this work, since it would introduce some of the aforementioned issues about information aging and priority, as in the case of multi-hop gossiping. Instead, we focus only on distribution techniques based on the assumption of an average non-zero number of neighbors in urban areas.

DOI: 10.1002/sat

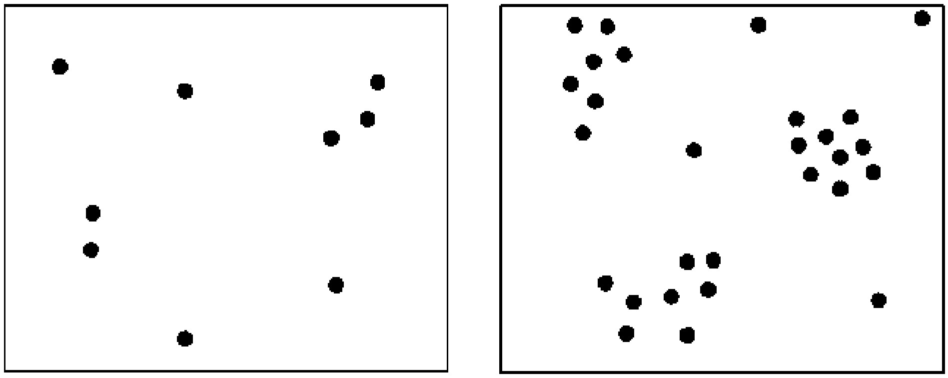

Figure 2. A sparse network on the left and a clustered network on the right.

In [27], the authors propose the *Heterogeneous Random Walk* (HRW) mobility model that captures the presence of clusters as well as the isolated nodes, and the correlation between the speed of the vehicles and the clustering factor. Figure 2 depicts the difference between a sparse and a clustered network: the latter is typical in urban areas. On average, inside a cluster, the nodes move slower than outside it, because a cluster is an area with a large density of nodes; instead, outside a cluster, the density of nodes decreases and, therefore, the average speed increases. The latter phenomenon has been highlighted in real mobility traces. Thus, the heterogeneous speed leads to the heterogeneous density of nodes, which is inversely proportional to the speed, as described in [27]. The low speed and the closeness among nodes inside a cluster facilitates the data exchange. Therefore, the presence of clusters, commonly found in urban areas, improves the effectiveness of cooperative algorithms.

A VANET can be modelled as a non-empty undirected graph G: in fact, we assume that if nodes a and b are within the communication range, then b receives data from a and vice versa, thus the overlay graph is undirected. The graph $G = (V, E)$ consists of a set of vertices V and a set of edges E. The neighborhood of a vertex v_i can be defined as $N_i = \{v_j : e_{ij} \in E\}$, where e_{ij} is the redirection edge connecting the vertexes v_i and v_j. Generally speaking, a vertex v_i of a digraph has indegree δ^i_{in} and outdegree δ^i_{out}, where $\delta^i_{out} \neq \delta^i_{in}$; if an undirected graph G is considered, then $\delta^i_{in} = \delta^i_{out} = \delta^i$. Estimating the average degree of the network requires the knowledge of the degree δ^i of each node. In case of a very large network (graph), this can prove computationally heavy;

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a solution to this comes from Network Science, which defines the average degree of a graph G as $<d> = 2E/|V|$, where $|V|$ is the cardinality of V. As far as different mobility models are to be considered for the purpose of performance comparison, the first assessment should characterize the different degree of the nodes when using HRW in place of MG and RW models. HRW model exhibits a larger $<d>$ than both MG and RW mobility models in the scenario under consideration, as proved in Section 6. It means that the average number of neighbors, whose definition is identical to $<d>$ for a non-empty undirected graph G [28], is larger in HRW than in both MG and RW mobility models. Thus, the use of a cluster-based mobility model, such as HRW, provides several advantages: for instance, it is more realistic than both MG and RW mobility models and, furthermore, it increases the probability of a correct decoding at receivers, thanks to the larger $<d>$ value.

When considering the use of HRW in our scenario, four different cases are possible: (*i*) a set of nodes originates a cluster that is inside the coverage area of an RSU; (*ii*) a set of nodes originates a cluster that is not covered by an RSU; (*iii*) a node is not inside a cluster, but is in the coverage area of an RSU; (*iv*) finally, a node is not part of a cluster and not covered by an RSU. Figure 1 shows the four cases so far discussed. The most favorable situation is the one described in Case (*i*): the nodes can take advantage of both situations, i.e., to be inside a cluster, which is equivalent to have a lot of slowly moving neighbors, and close to an RSU. Instead, Case (*iv*) represents the worst situation: a node is isolated and can only rely on the satellite channel. If RSUs are removed, as we foster in this work, Case (*i*) cannot be considered (because of the presence of an RSU), thus Case (*ii*) represents the best scenario for data distribution via gossiping.

4.2. Satellite channel

In our scenario, the satellite signal is received by mobile and fixed nodes in an urban area. Mobile nodes and RSUs are equipped with DVB-SH radio interfaces. A LMS channel, such as the one under consideration, is affected by shadowing and fading effects: it can be impaired by obstacles in the propagation path (buildings, bridges, trees, etc.), which can cause a strong attenuation. Furthermore, multipath fading occurs because the antenna of mobile users cannot be highly directive; thus, the

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satellite signal is received not only via the direct path, but also after being reflected by the objects in the surroundings. Due to different propagation distances, multipath signals may add destructively, thus resulting in a deep fade. In [23] and in [29], the LMS channel model in [30] is reduced to a two-state Discrete Time Markov Chain model (DTMC). The latter assumes a lossless good state (G) in Line of Sight (LoS) (or, equivalently, a residual uncorrelated error probability), whereas the shadowing and blocking states are grouped together in a bad state (B) in Non Line of Sight (NLoS), which causes erroneous packet receptions (or, equivalently, a negligible success probability). The propagation conditions can be classified in urban, suburban and rural conditions. In urban and suburban environments, the main cause of channel impairment is the long-lasting shadowing due to buildings that causes intermittent satellite connectivity; in rural conditions, the main cause of impairment is the tree shadowing.

DVB-SH standard supports the use of MPE-IFEC techniques [26], an enhanced FEC module implementing Raptor codes [31]. The DTMC process that represents the channel behavior is characterized by the following transition matrix T:

$$T = \begin{pmatrix} B & 1-B \\ 1-G & G \end{pmatrix} = \begin{pmatrix} 1-p_l\,(1-\rho) & p_l\,(1-\rho) \\ (1-\rho)\,(1-p_l) & p_l+\rho\,(1-p_l) \end{pmatrix} \tag{1}$$

where p_l is the average stationary MPE-IFEC symbol loss rate and ρ is the correlation factor.

In the following, we assume that each MPE-IFEC block carries exactly a RLNC symbol. In fact, before the satellite broadcasting, RLNC techniques are applied, with a code rate $R_1 = k/n_1$; thus, n_1 RLNC symbols are carried by the same number of MPE-IFEC blocks. Therefore, the loss probability of an MPE-IFEC block, here referred to as $BLER_{SAT}$, corresponds to the loss probability of an RLNC symbol in the DVB-SH channel. Given the two-state LMS channel model in (1) and a MPE-IFEC code (N, K), with code rate $K/N < 1$ and redundancy $R = N - K > 0$, it is possible to derive $BLER_{SAT}$ from p_l with an approach similar to the one proposed by equation (7) in [32]. We define $P_n(j)$ as the probability of being for j times in the bad state B during n consecutive time instants (i.e., the probability of losing j packets over consecutive n ones) as in the

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following expression:

$$P_n(j) = \begin{cases} (1-p_l)(1-B)^{N-1} & j = 0 \\ p_l\big(P_n^{BB}(j) + P_n^{BG}(j)\big) + (1-p_l)\big(P_n^{GB}(j) + P_n^{GG}(j)\big) & 1 \le j < N \\ (1-p_l)(1-G)^{N-1} & j = N \end{cases} \tag{2}$$

where $P_n^{BB}(j)$, $P_n^{BG}(j)$, $P_n^{GB}(j)$, and $P_n^{GG}(j)$ are defined as follows:

$$P_n^{BB}(j) = \sum_{i=2}^{\min(j,N-j+1)} B^{i-1}G^{i-1}\binom{j-1}{i-1}(1-G)^{j-i}(1-B)^{N-j-i+1}\binom{N-j-1}{i-2}$$

$$P_n^{GG}(j) = \sum_{i=2}^{\min(j+1,N-j)} B^{i-1}G^{i-1}\binom{j-1}{i-2}(1-G)^{j-i+1}(1-B)^{N-j-i}\binom{N-j-1}{i-1}$$

$$P_n^{BG}(j) = \sum_{i=1}^{\min(j,N-j)} B^{i-1}G^{i}\binom{j-1}{i-1}(1-G)^{j-i}(1-B)^{N-j-i}\binom{N-j-1}{i-1}$$

$$P_n^{GB}(j) = \sum_{i=1}^{\min(j,N-j)} B^{i}G^{i-1}\binom{j-1}{i-1}(1-G)^{j-i}(1-B)^{N-j-i}\binom{N-j-1}{i-1}.$$

The following equation provides the analytical expression of the Block Error Rate (BLER) in the satellite channel, where we consider that decoding fails if more than R packets are lost:

$$BLER_{SAT} = \sum_{j=R+1}^{N} P_n(j)\frac{j}{N}, \tag{3}$$

Thus, each node on the ground independently [33] receives $r \in [0,\, n_1]$ RLNC symbols after the MPE-IFEC decoding.

In the following section, we provide the vehicular channel model and discuss how the received MPE-IFEC blocks are forwarded in the vehicular channel thanks to the gossiping algorithm in use.

4.3. IEEE 802.11p channel

The vehicular terminals considered in this work, equipped with OBUs, are not energy constrained, and capable of as much computation power and memory as needed in this scenario. According

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to [34], there is a negligible spatial correlation among the mobile nodes in an urban vehicular network due to mobility and multipath propagation: therefore, we assume that each link between any couple of vehicular nodes is independent of one another. Each node is set in promiscuous mode for receiving any transmission in its communication range. Each data transmission is affected by the loss probability p^v_{loss} due to shadowing and fading effects, and by the collision probability p^v_{coll}. $BLER_{VEH}$ is defined as the loss probability of a RLNC symbol in the 802.11p channel, as in the following equation:

$$BLER_{VEH} = p^v_{loss} + p^v_{coll} - p^v_{loss}\, p^v_{coll}. \tag{4}$$

In order to trigger gossiping with probability p_g, at least k RLNC symbols must be received[§] from satellite, which occurs with probability $p_{r\geq k}$, as follows:

$$p_{r\geq k} = \sum_{i=k}^{n_1} \binom{n_1}{i} BLER^i_{SAT} \left(1 - BLER_{SAT}\right)^{n_1 - i} \tag{5}$$

Thus, each gossiping node receives $k' \in [k, n_1]$ RLNC symbols. In the following, we assume that, if $k' > k$, only the first k symbols are selected for gossiping. Prior to gossiping, each node recodes the k symbols with a rate $R_2 = k/n_2$. The total number of RLNC symbols that $<d>$ neighbors send to a mobile node is defined as:

$$h = \frac{k}{R_2}\, p_g <d> p_{r\geq k} = \frac{k}{R_2}\, \eta = n_2\, \eta \tag{6}$$

where $\eta = p_g <d> p_{r\geq k}$ is the actual number of gossiping neighbors over $<d>$ potential ones.

In the following, we provide the analytical models to estimate p^v_{loss} in Section 4.3.1 and p^v_{coll} in Section 4.3.2. The former is based on PLA (Physical Layer Abstraction) approach [35], and the latter is based on the analytical approach in [36].

4.3.1. *Physical Layer Abstraction - RBIR approach*

In [37], a measurement campaign is reported, based on the use of Dedicated Short Range

[§] In order to correctly decode a coded transmission, at least k RLNC independent linear combinations must be received. Here, we are not assuming independence among the k symbols, thus receiving k RLNC symbols is not equivalent to say that a generation can be correctly decoded. Anyway, it is worth noting that, in the presence of a large enough GF (of size $q \geq 2^8$), the probability that any k random combinations are linearly independent is close to one [9].

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Communication (DSRC)/IEEE 802.11p prototype radio interfaces at 5.9 [GHz]. The main contribution in [37] is a dual slope model for the path loss in urban V2X scenarios, based on real measurements. Here, the models in [37, 38] are adopted for the path loss simulator. An Orthogonal Frequency-Division Multiplexing (OFDM) signal with 52 carriers (48 information carriers) and a convolutional encoder with rate $1/2$ are in use. We assume a finite fixed communication range. PLA has been implemented to simulate the vehicular channel, as proposed in the Received Bit Information Rate (RBIR) approach. The purpose of PLA is to predict the corresponding BLER, here denoted as p^v_{loss}, according to the instantaneous channel state information [35]. In fact, the RBIR model measures the symbol mutual information (SI) for a Single Input Single Output (SISO)/Single Input Multiple Output (SIMO) system, which is given by:

$$
\begin{aligned}
SI(SNIR_s, m(s)) &= \log_2 M - \frac{1}{M}\sum_{m=1}^{M} E_U = \\
&= \left\{ \log_2 \left[1 + \sum_{k=1,k\neq m}^{M} exp\left(- \frac{|X_k - X_m + U|^2 - |U|^2}{1/SNIR_s} \right) \right] \right\},
\end{aligned}
\tag{7}
$$

where U is a *r. v.* extracted from a complex normal distribution with mean equal to zero and variance equal to $1/(2\,SNIR_s)$ per component, M the size of the modulation constellation, $SNIR_s$ the Signal to Noise plus Interference Ratio (SNIR) at the s-th symbol (or sub-carrier), and $m(s)$ the number of bits at the s-th symbol. The normalized RBIR, when C sub-carriers are used to transmit a coded block, is given by:

$$
RBIR = \frac{\sum_{s=1}^{C} SI(SNIR_s, m(s))}{\sum_{s=1}^{C} m(s)}. \tag{8}
$$

We define p^v_{loss} as follows:

$$
p^v_{loss} = \frac{1}{2} erfc[(RBIR - \alpha_1)/\alpha_2], \tag{9}
$$

where α_1 and α_2 are two parameters that provide a close fit to the Additive White Gaussian Noise (AWGN) performance curve and $erfc(\cdot) = 1 - erf(\cdot)$ is the *complementary error function*. The aforementioned p^v_{loss} formulation is similar to the one in [39]. For instance, if QPSK 1/2 is in use, $\alpha_1 = 0.5512$ and $\alpha_2 = 0.0434164$. The system parameters used for the PLA implementation in this work are readable in Table II. According to those values and to the RBIR expression in (8), p^v_{loss}

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Parameter	Value
V2X carrier frequency	5.9 [GHz]
V2X transmission power	16 dBm
Number of 802.11p OFDM carriers	52
802.11p subcarriers spacing	0.15625 [MHz]
MCS	QPSK 1/2

Table II. Settings of the 802.11p-based vehicular channel

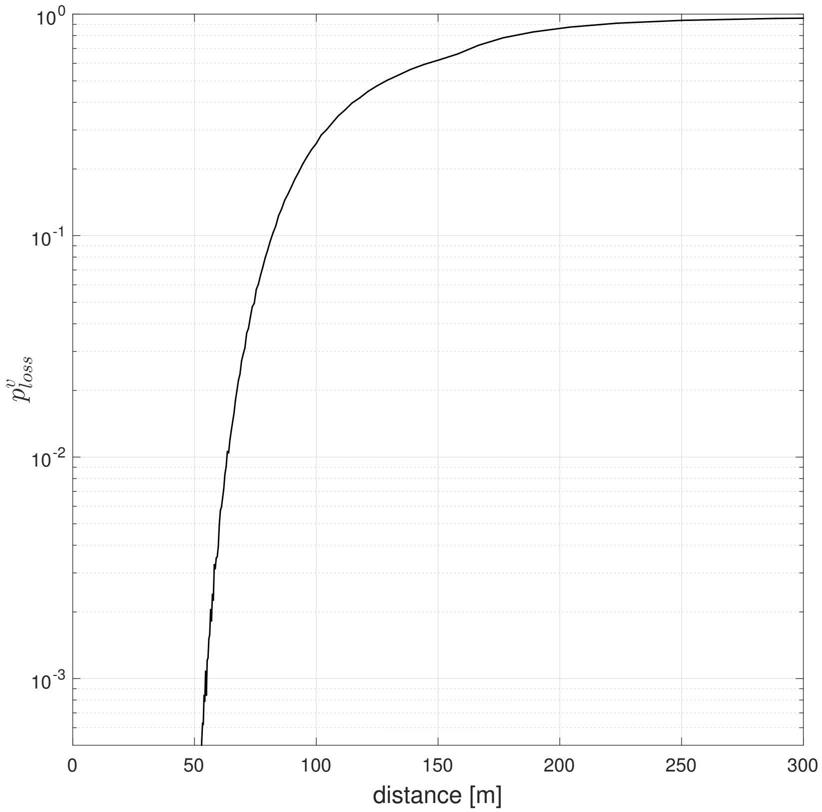

Figure 3. p^v_{loss} versus distance, in meters, between two mobile nodes in the vehicular segment

can be read in Figure 3 as function of the distance, measured in meters between two nodes, when assuming a noise floor of -90.4 dBm.

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4.3.2. Collision probability

The medium access mechanism of IEEE 802.11 standard relies on a carrier sense multiple access with collision avoidance (CSMA/CA) algorithm to mediate the access to the shared medium. Briefly, a backoff time is chosen randomly from a contention window of length W [slots], whose range is $[W_{min}, W_{max}]$. W is doubled after each unsuccessful transmission, up to the maximum value equal to $(W_{max} + 1)$. In [36], a two-dimensional Markov chain of $(b + 1)$ backoff stages is used to model the backoff time of a node. In [36], the model assumes that each packet collides in a slot time with constant and independent probability p^v_{coll}, i.e., at least one of the η neighbors contending the channel transmits in the same slot time. Therefore, if each of the η nodes transmits a packet, with channel access probability π in steady state¶, p^v_{coll} can be written as follows:

$$p^v_{coll} = 1 - (1 - \pi)^\eta. \tag{10}$$

π is derived in [36] as a function of the number of backoff stages b, of the minimum contention window value W_{min}, and of the collision probability p^v_{coll} as follows:

$$\pi = \frac{2}{1 + W_{min} + p^v_{coll}\, W_{min} \sum_{j=0}^{b-1} (2\, p^v_{coll})^j}. \tag{11}$$

The system of non linear equations coming from (10) and (11) allows a unique solution (p^v_{coll}, π), which can be numerically computed, by using the 802.11p parameters in Table III, accordingly to [40].

5. COVERAGE PROBABILITY

In this section, we provide the analytical formulation of the coverage probability, or full coverage, as previously defined in Section 4. We recall that a code rate R_1 is applied to a RLNC generation before the satellite broadcasting: thus, RLNC techniques at the remote source are applied equivalently to a FEC code, just above the MPE-IFEC scheme, hence increasing the probability of a correct decoding at the destination. In the vehicular segment, RLNC recoding with rate R_2 is done before

¶In the following, we assume that each gossiping node has always a packet ready for transmission.

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Parameter	**Value**
W_{min}	15 slots
W_{max}	1023 slots
b	$\log_2 \frac{W_{max}+1}{W_{min}+1}$
slot time	13 [μs]

Table III. 802.11p simulator settings

gossiping with probability p_g, if at least k RLNC symbols have been received. It is worth noting that the satellite and the vehicular channels typically show different loss rates, which opens to the possibile RLNC recoding feature in VANET, in order to adapt to different channel conditions. The reliable delivery of data relies on two mechanisms: a proactive coding, based on end-to-end RLNC techniques, and a gossiping strategy in VANET.

In order to correctly decode, at least k independent RLNC symbols must be received. The cumulative distribution function of the probability of receiving k independent symbols is provided in [41] as follows:

$$\begin{cases} P_{ns}(n,k) = \prod_{j=0}^{k-1} \left(1 - \frac{1}{q^{n-j}}\right), & n \geq k \\ P_{ns}(n,k) = 0, & n < k \end{cases} \tag{12}$$

where $q = 2^x$ is the Galois field size and n the coded symbols, $n \geq k$. Therefore, the RLNC decoding probability after gossiping can be derived as follows:

$$P_{dec}^{RLNC}(n,k,BLER_{VEH}) = \sum_{j=k}^{n} \binom{n}{j} BLER_{VEH}^{j} (1 - BLER_{VEH})^{n-j} P_{ns}(j,k). \tag{13}$$

Analogously, the decoding probability of the RLNC symbols received from the satellite is given by $P_{dec}^{RLNC}(n_1,k,BLER_{SAT})$. Therefore, a node can decode a RLNC generation worth of k symbols if: (*i*) the decoding of the symbols received via satellite is possible, according to $P_{dec}^{RLNC}(n_1,k,BLER_{SAT})$; (*ii*) if the decoding of the symbols received from the gossiping neighbors is possible, according to $P_{dec}^{RLNC}(n,k,BLER_{VEH})$. Eventually, we can define the global

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decoding probability, or *coverage probability*, as follows:

$$\begin{aligned} P_{cov}^{RLNC}(n, n_1, k) = & P_{dec}^{RLNC}(n_1, k, BLER_{SAT}) + P_{dec}^{RLNC}(n, k, BLER_{VEH}) + \\ & - P_{dec}^{RLNC}(n_1, k, BLER_{SAT}) P_{dec}^{RLNC}(n, k, BLER_{VEH}). \end{aligned} \tag{14}$$

Therefore, when RLNC techniques are in use, a *full coverage level* is equivalent to having $P_{cov} = P_{cov}^{RLNC}(n, n_1, k) \geq 0.99$.

6. PERFORMANCE EVALUATION

A custom simulator‖ has been developed to test the scenario under consideration. The following numerical results are obtained considering a set of $|V| = 150$ nodes in an urban area $A = 1$ [km^2] and the average vehicle speed is of 10 [m/s]. The LMS channel model in use is described in Section 4.2, and we assume a duration of the G state of ≈ 22 [s] and a duration of the B state of ≈ 15 [s], similarly to the empirical measurements provided in [29]. The MPE-IFEC module uses a Raptor code [31] with rate $(N, K) = (255, 170)$ and a symbol length of 1 [KB]. Furthermore, the ON-OFF LMS channel model is derived from [23] and the DVB-SH link layer specifications lead to an average stationary MPE-IFEC symbol loss rate $p_l \approx 36\%$ and a correlation factor $\rho \approx 0.996$.

Mobility model	**Average degree** $<d>$	**Normalized average degree**
Random Walk (RW)	≈ 16	1
Manhattan Grid (MG)	≈ 17	1.06
Heterogeneous RW (HRW)	≈ 27	1.7

Table IV. Average degree of MM, RW, and HRW mobility models when simulating $|V| = 150$ mobile nodes in an urban area of 1 km^2.

‖ Our simulator has been validated by ensuring an exact match between the numerical values herein provided and the results in [41]. Furthermore, our numerical results are obtained from extensive simulation runs, in order to be confident on their statistical reliability.

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Table IV shows the average degree $<d>$ of MG, RW and HRW mobility models.The MG and RW mobility models show a similar $<d>$ value: it means that, on average, the number of the neighbors of each node is approximately the same. The most outstanding difference in mobility between RW and MG models is in the way the nodes move: when using RW, each node can be in any point of the map, with no spatial constraints; instead, when using MG, the nodes move accordingly to a squared road system. Even considering the aforementioned difference, these two mobility models show comparable $<d>$ values: therefore, according to the said metric, the two mobility models are almost indistinguishable. Instead, when using the HRW mobility model, the $<d>$ value is approximately 1.7 times larger than in the other cases: this is due to the clustering phenomenon, common in urban areas. Therefore, we only consider the use of the HRW model in the following performance evaluation.

Furthermore, we provide the coverage probability P_{cov} in three different scenarios, assuming a generation size $k = 4$:

1. *RSUs* scenario: in Section 6.1, we estimate the needed RSU density in order to satisfy the requirement on P_{cov}. No gossiping is done in this scenario;
2. *VC + RSUs* scenario: in the scenario considered in Section 6.2, gossiping is done without recoding, and we estimate the minimum p_g that guarantees full coverage. Different RSU densities are taken into account and numerical results are provided;
3. *VC + RLNC*: in Section 6.3, we remove RSUs from the urban area, while enabling recoding; thus, we estimate the minimum needed p_g at different R_2 rates.

Then, the three scenarios are compared in Section 6.4. In order to understand the impact of the generation size k on the coverage probability P_{cov}, we provide numerical results on the relation between k and the average number of neighbors $<d>$ in Section 6.5. The chosen generation size provides multiple advantages, for the following reasons: it ensures short buffering delays before coding/decoding processes. Furthermore, as proved in [42], the packet overhead and the matrix size are reduced, resulting in a lower impact on the available resources of the network and of the mobile nodes. In addition, it provides low computational costs and low energy requirements.

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6.1. RSU scenario

In this scenario, we provide the P_{cov} as a function of the number of RSUs and the probability $P_{dec}^{RLNC}(n_1, k, BLER_{SAT})$; thus, no gossiping is done in the terrestrial part. We assume that the LMS channel between an RSU and the satellite is always in G state. Each RLNC block received by an RSU is forwarded to the $<d>$ neighbors in proximity and a mobile node can decode only if it receives the whole generation from the satellite or from an RSU, due to the absence of cooperation. We also assume that RSUs are placed in a regular grid and the transmission frequencies of RSUs are chosen differently one from another, in order to avoid collisions among RSUs. In the absence of overlapping among the coverage areas of RSUs, but with the whole area fully covered, we assume an RSU density $\gamma = 1$: this is equivalent to place approximately 44 RSUs in the urban area under consideration. Figure 4 shows P_{cov} versus RSUs density in this scenario for different R_1 rates. When $R_1 = 1/2$, full coverage can be achieved even in the absence of RSUs but halving the information rate. Instead, if $R_1 = 2/3$ or if $R_1 = 4/5$, the presence of RSUs is needed to ensure coverage: the larger the code rate, the larger the need of RSUs, in order to satisfy the requirement on P_{cov}.

Each RSU has a fixed cost for installation and maintenance, and a large number of them may be needed to ensure full coverage. In order to remove the need for RSUs, and therefore lowering the cost of such a setup, we investigate the benefits provided by the terrestrial cooperation in Section 6.2.

6.2. VC+RSUs scenario

In this scenario, the mobile nodes on the ground gossip the RLNC symbols received from the satellite. No recoding is done, which is equivalent to having $h = k\eta$ in (6). Figure 5 shows the numerical results: each plot begins at the minimum p_g that is necessary to have, on average, at least one neighbor (be it a RSU or a mobile node), in order to exploit the advantages that gossiping can provide. Three different γ values, from 0.0225 to 1, have been taken into account, in order to show the incremental advantage provided by their presence on the ground. Furthermore, only code rates $R_1 = 2/3$ and $R_1 = 4/5$ are taken into account, because the use of a code rate $R_1 = 1/2$ does

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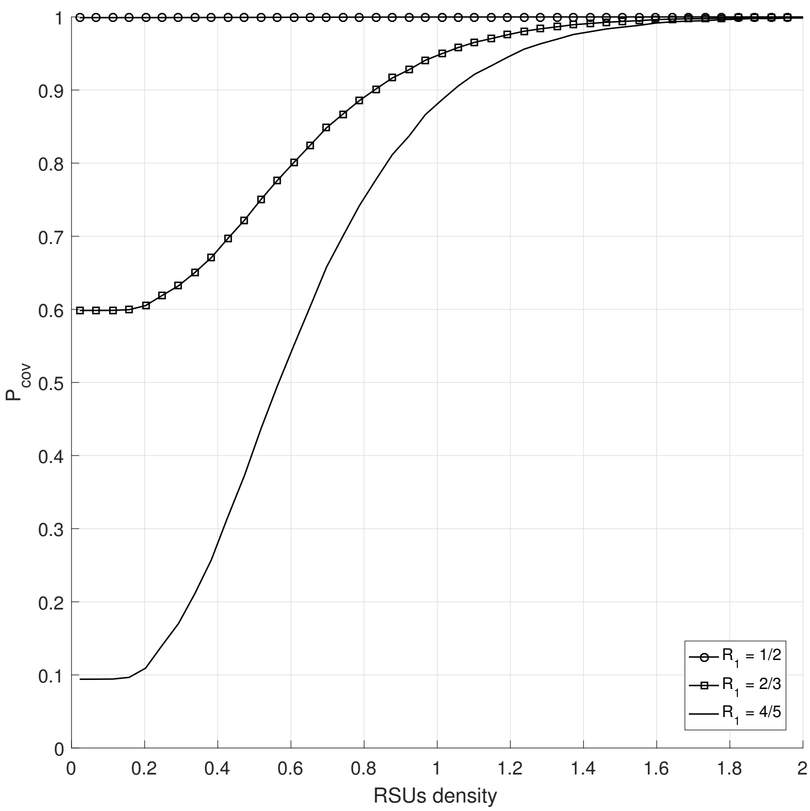

Figure 4. RSUs scenario: P_{cov} as a function of the RSUs density γ

not require neither RSUs nor gossiping to guarantee the required P_{cov}, as shown in Figure 4. The minimum p_g ranges into $[0.4, 0.45]$ for a code rate $R_1 = 2/3$; instead, for a code rate $R_1 = 4/5$, the minimum p_g ranges into $[0.45, 0.55]$. It is worth noting that, for a fixed R_1, as p_g increases, the benefits provided by the presence of RSUs decreases: in fact, the plots converge to the same P_{cov}^{VC+RSU} value.

In Section 6.3, the RSUs are removed in order to evaluate if full coverage can still be guaranteed at a price of a larger gossiping probability.

6.3. VC + RLNC scenario

In this scenario, recoding is done before gossiping and RSUs are removed from the urban area. Thus, the mobile nodes rely only on the neighbors to correctly receive data if decoding the satellite

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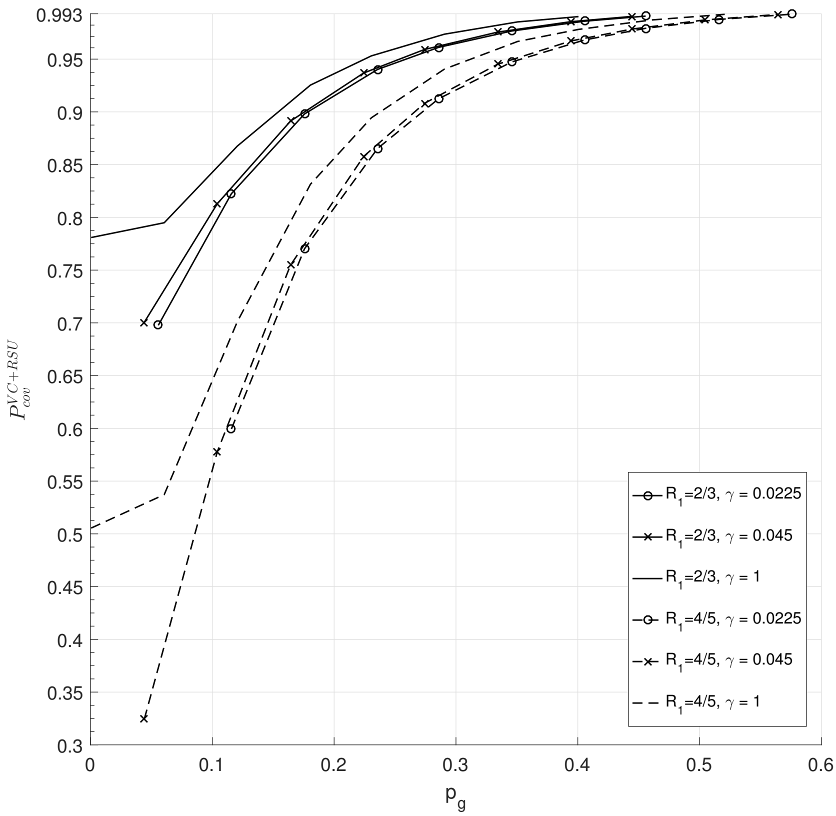

Figure 5. VC + RSUs scenario: P_{cov}^{VC+RSU} as a function of p_g at different γ values

transmission has failed. The number of gossiping nodes is η, according to (6), and each node recodes the received RLNC symbols with rate $R_2 = k/n_2$, where n_2 can be chosen accordingly to the channel statistics or to the target p_g. In fact, if a receiver is able to collect k independent RLNC symbols, then it is able to decode the RLNC generation: k symbols can be collected from a single neighbor (low p_g, large n_2) or from multiple neighbors (high p_g, low n_2), and p_g can be tuned accordingly to the chosen n_2 value, or vice versa. In the following, we show the numerical results for n_2 ranging into $[1, 8]$, which are the random linear combinations sent to $<d>$ neighbors from each mobile node that has collected at least k symbols. The larger the number of gossiping nodes, the larger the collision probability that can prevent the correct reception of gossiped symbols; thus, a trade-off must be identified, in order to satisfy the requirement on P_{cov}^{RLNC}. The numerical results are shown in Figure 6 for rates $R_1 = 2/3$ and $R_1 = 4/5$: it is visible how reducing n_2 requires a

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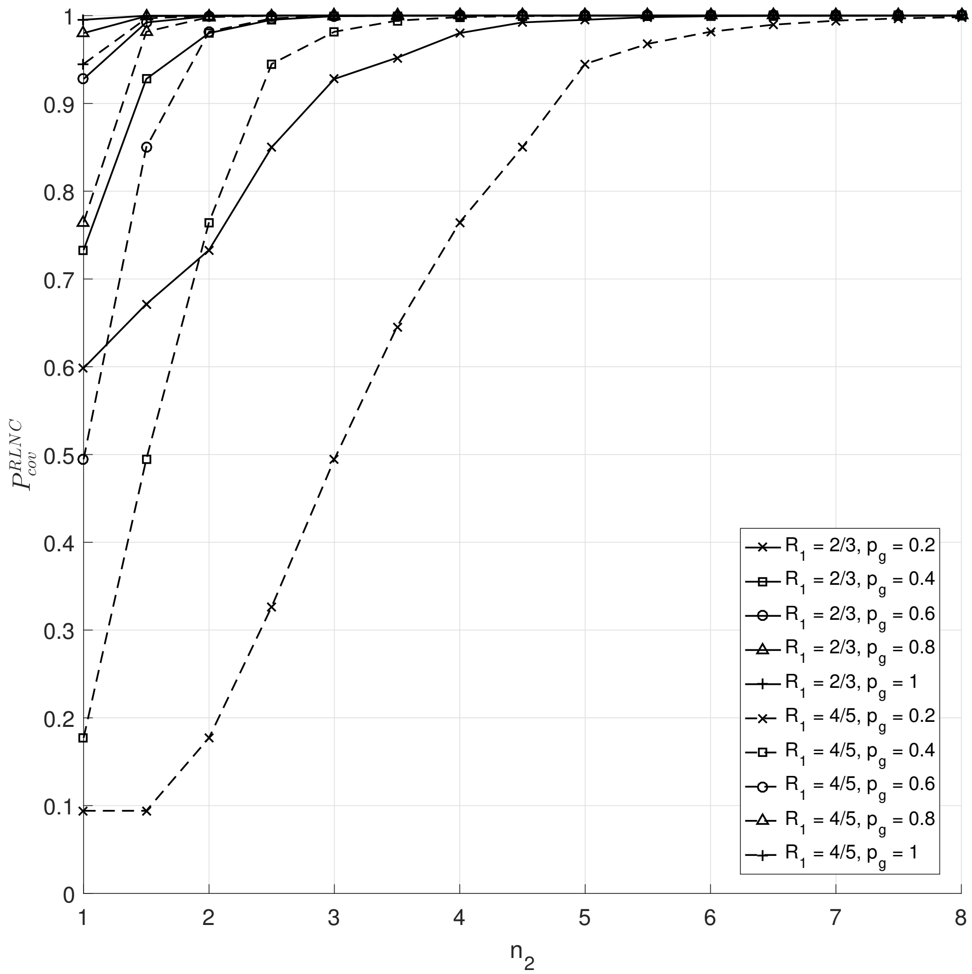

Figure 6. Probability of coverage P_{cov}^{RLNC}, in the absence of RSUs, versus the number of recoded linear combinations sent by a source node to $<d>$ neighbors

larger p_g (and vice versa) to satisfy the requirement on the target coverage probability. In Figure 6, the values (p_g, n_2), needed to reach the target coverage probability, range into $[(0.2, 5.5), (1, 1.5)]$ for a code rate $R_1 = 2/3$; instead, for a code rate $R_1 = 4/5$ (p_g, n_2) ranges into $[(0.2, 8), (1, 2)]$.

In order to better understand the advantages brought by the use of RLNC techniques (or, alternatively, by the presence of RSUs, as discussed in Section 6.2), we compare the achieved P_{cov}^{VC+RSU} with P_{cov}^{RLNC} in the same p_g range: the former is visible in Figure 5, the latter in Figure 6. At a rate $R_1 = 2/3$, for $p_g = 0.4$, an RSU density $\gamma = 1$ is needed to target the desired P_{cov}^{VC+RSU};

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if $p_g = 0.45$, γ decreases to 0.0225. Instead, for the same p_g values and rate R_1, from $n_2 = 0.5$ to $n_2 = 3$ linear combinations must be sent per gossiping node in absence of RSUs, in order to satisfy the requirement on P_{cov}^{RLNC}. At a rate $R_1 = 4/5$, for $p_g = 0.45$, the minimum RSU density is $\gamma = 1$; for $p_g = 0.55$, the minimum RSU density decreases to $\gamma = 0.0225$. Instead, for the same p_g values and rate R_1, from $n_2 = 3$ to $n_2 = 4$ linear combinations must be sent per gossiping node, in the absence of RSUs. Thus, respecting the requirement on P_{cov} is possible while contemporarily removing the need for RSUs: a proper set of the n_2 and p_g values is sufficient to guarantee the desired coverage probability. It is worth noting that using RLNC techniques increases the computational cost at the sender and at the receiver w.r.t. to the scenarios in Sections 6.1 and 6.2, because of coding/decoding operations and the relative overhead must be taken into account due to the NC header. Anyway, those drawbacks are negligible if compared with the cost of installing any fixed hardware equipment on the ground, such as CGC/RSUs.

6.4. *Comparison among the three scenarios under consideration*

In this section, we compare the three different scenarios, in order to understand the amount of circulating traffic in the terrestrial segment needed to satisfy the requirement on the coverage probability. In Table V, we provide the average number of symbols that each gossiping node must forward to its neighbors in each considered scenario. In the first row, the RSUs scenario is analysed: this is the most expensive scenario, because the coverage probability depends only on the presence of RSUs, whose installation has a fixed cost; on the other hand, this scenario has the lowest number of symbols forwarded by each fixed node to the mobile nodes.

In the second row of Table V, the scenario VC + RSUs is analyzed: here, the RSUs density is strongly reduced and the mobile nodes cooperate with one another: this allows reducing the overall cost of the system at the price of a non-zero gossiping probability. In turns, this means that the number of symbols that each node forwards to its neighbors must increase with respect to the RSUs scenario. A consideration is here in order on the gossiping probability p_g: a value close to one means that the collision probability in the vehicular channel may be striking, causing the loss of

Scenario	**Sent packets per node** h/η	**Parameter values per rate** R_1	h/η	η
RSUs	k	$p_g = 0$, $\gamma = 1.7$, $R_1 = 2/3$	4	1
		$p_g = 0$, $\gamma = 2$, $R_1 = 4/5$	4	1
VC + RSUs	$k\,(1 + 1/\eta)$	$p_g = 0.4$, $\gamma = 0.02$, $R_1 = 2/3$	4.4	≈ 8
		$p_g = 0.6$, $\gamma = 0.02$, $R_1 = 4/5$	4.6	≈ 11
VC + RLNC	n_2	$p_g = 1$, $n_2 = 1.5$, $R_1 = 2/3$	1.5	≈ 16.7
		$p_g = 1$, $n_2 = 2$, $R_1 = 4/5$	2	≈ 16.7

Table V. Average numerical value of the packets that each (fixed or mobile) node sends to its neighbors in order to reach the target coverage probability in the scenarios under consideration

several packets, thus requiring a larger n_2 value to counteract it. On the other hand, the use of fixed equipment to reduce p_g is expensive, and must be carefully evaluated. In the authors' opinion, the *price* of collisions is much lower than the actual cost of installing any fixed equipment, thus the use of RLNC techniques must be preferred over CGC/RSUs, even in presence of a possibly high collision rate.

In the last row of Table V, the scenario VC + RLNC is analysed: here, removing the need for RSUs provides a further cost reduction, at the price of an increasing gossiping probability p_g, i.e., a larger terrestrial cooperation among the mobile nodes.

A larger p_g implies a larger spatial cooperation, where also groups of few isolated nodes may have a higher probability to correctly decode data; on the other hand, a higher number of symbols n_2 forwarded per node provides larger redundancy, thus more robustness to losses, which can prove to be useful if the vehicular channel is prone to high loss/collision rates. Thus, the need for RSUs can be completely removed in the scenario under consideration in this work, and the target coverage probability can be reached with proper settings of the gossiping probability, code rate R_1 before satellite broadcasting, and recoding rate R_2 before gossiping. The use of a realistic mobility model, such as the HRW model here taken as reference, helps in better understanding the advantages that RLNC techniques can offer in urban areas for reliable satellite broadcast applications.

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6.5. The relation between the generation size and the average number of neighbors

In this section, we analyze the relation between k and $<d>$ and its impact on the coverage probability. We focus on the last proposed scenario, that is without the use of RSUs. We recall that, when RLNC is used, a receiver collects coded symbols from its $<d>$ neighbors, thanks to gossiping: if the receiver succeeds in collecting at least k independent symbols of a generation, then a successfully decoding phase is possible; otherwise, decoding fails. In the following, we assume a fixed generation size k and a variable number n_2 of RLNC packets generated by $<d>$ source encoders. The number of neighbors $<d>$ is here intended as a parameter, and we are interested in evaluating how the coverage probability varies, by varying the ratio $k/<d>$. It is also worth noting that the following results depend on the chosen coding ratios (R_1, R_2); hence, what follows aims at presenting the relationship between the generation size and the number of neighbors. As expected, the larger the number of neighbors, the larger the probability of correctly decoding the intended packets in presence of gossiping, because a large number of RLNC packets are received by each vehicle, on average. The lower the ratio $k\,/<d>$, the higher the probability to correctly decode a generation, even for low p_g and n_2 values. In order to prove the latter, we provide P_{cov}^{RLNC} in Figures 7 and 8 for code rates $R_1 = 2/3$ and $R_1 = 4/5$, respectively, for an increasing $k\,/<d>$ ratio.

Figure 7 shows that a RLNC generation worth of $k \approx 1.48 <d>$ symbols can be decoded with a very high probability if $p_g = 1$ and $n_2 = 8$. We recall that, here, a coding ratio $R_1 = 2/3$ is applied to data before satellite broadcasting. If the $k\,/<d>$ ratio still increases, a correct decoding is unlikely to occur, as shown in the last plot ($k\,/<d> = 1.8519$) of Figure 7. If the coding ratio is $R_1 = 4/5$, as in Figure 8, then a RLNC generation worth of $k \approx 0.52 < d >$ symbols can be decoded with a very high probability if $p_g = 1$ and $n_2 = 8$. Increasing the $k\,/<d>$ ratio beyond ≈ 0.52 may prevent a correct decoding, as shown in the last two plots of Figure 8. Thus, the generation size and the coding/recoding ratios have a clear impact on the coverage probability, once the average number of neighbors is known.

Conversely, if the generation size is fixed, as well as coding/recoding ratios, then the number of neighbors should be larger than a minimum threshold in order to correctly decode data. Figures 7

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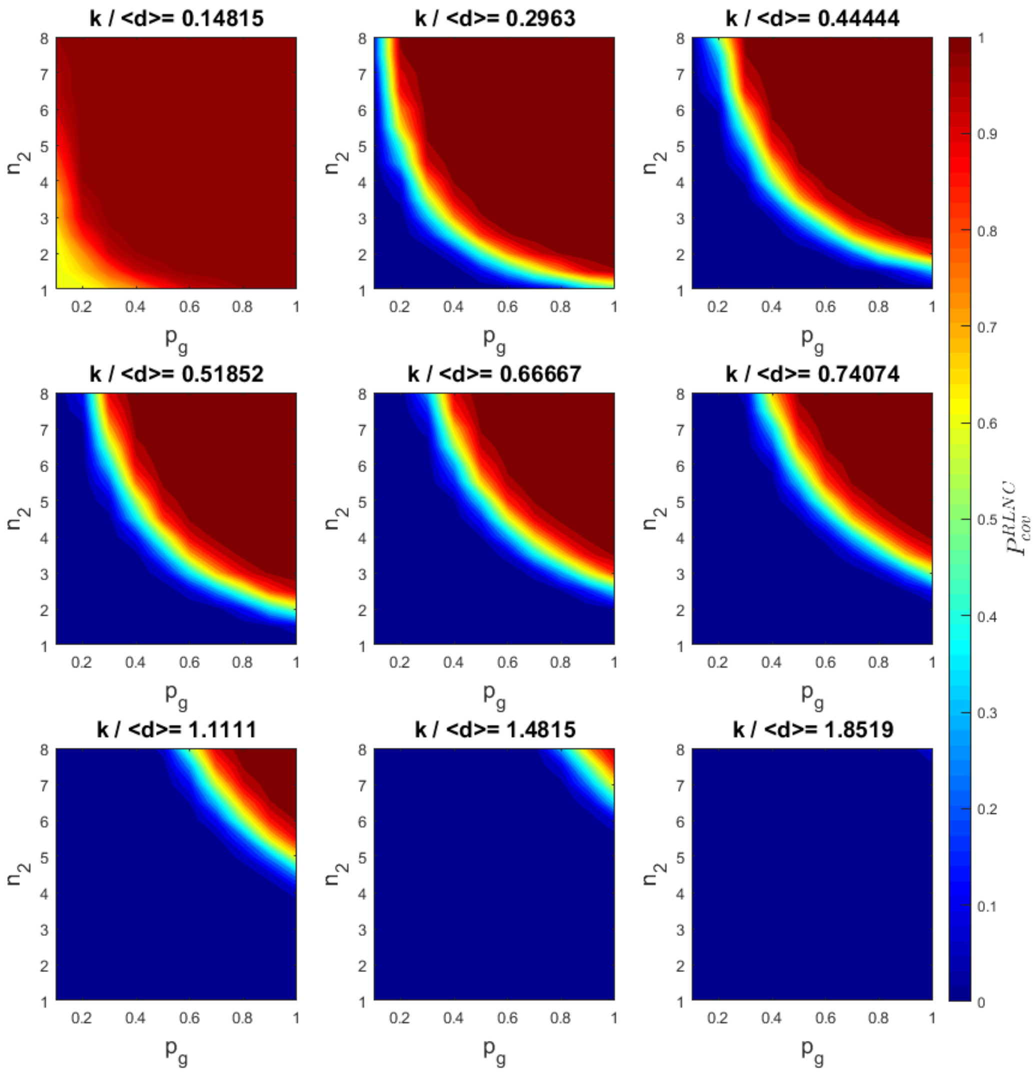

Figure 7. Coverage probability as a function of the generation size and the average number of neighbors for an increasing ratio $k\,/{<}d{>}$, when $R_1 = 2/3$

and 8 show how these parameters are strictly linked to one another. In fact, if the generation size and the coding/decoding ratios are fixed, then the number of neighbors ${<}d{>}$ depends on the previous settings: for instance, if considering the sub-plot in Figure 7 for $k/{<}d{>} = 0.74074$, then ${<}d{>} \approx 5.4$ for $k = 4$. It means that at least 5.4 neighbors are needed, on average, in order to correctly decode data for that generation size. Furthermore, the subplot gives information about the minimum values

DOI: 10.1002/sat

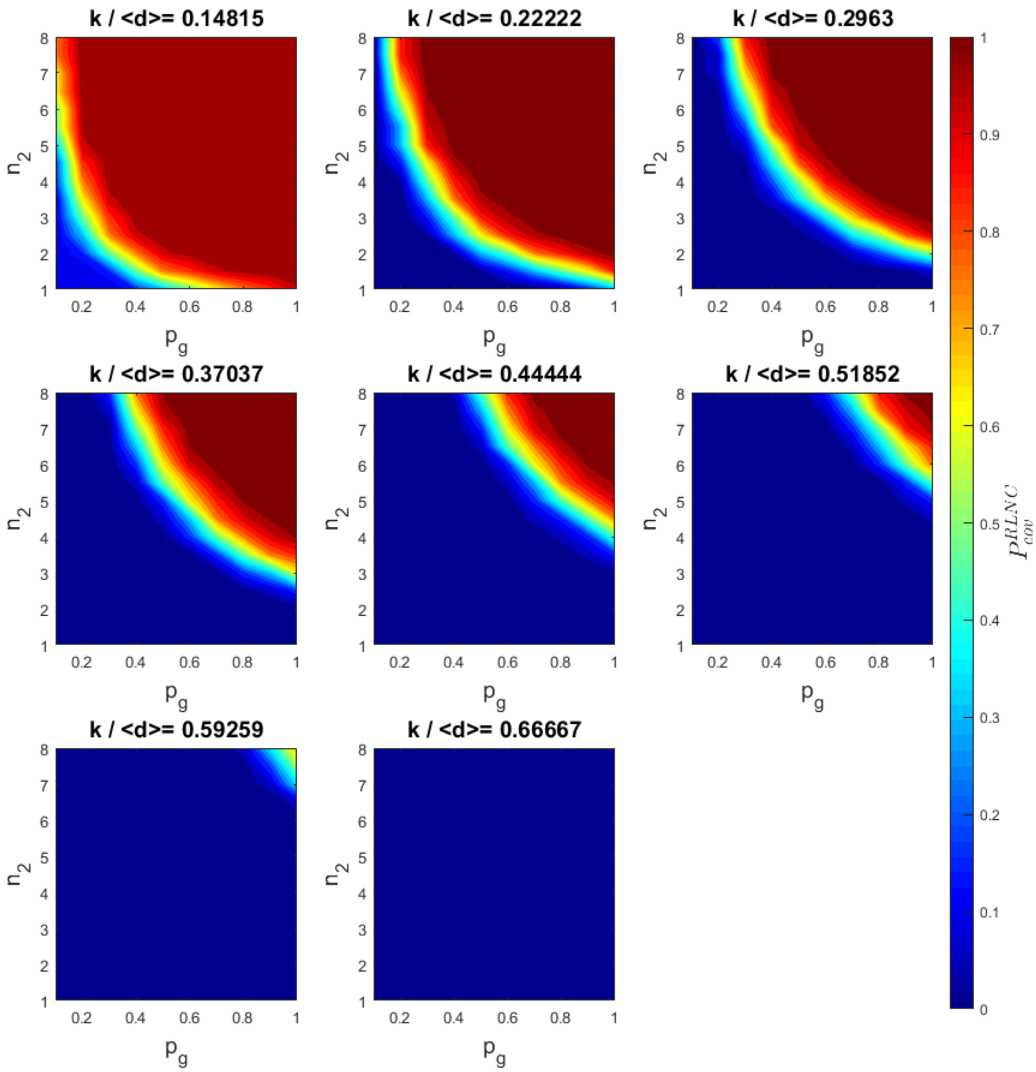

Figure 8. Coverage probability as a function of the generation size and the average number of neighbors for an increasing ratio $k\,/{<}d{>}$, when $R_1 = 4/5$

of the couple (p_g, n_2): those values are important to estimate the actual collision rate in the 802.11p-based network.

The average number of neighbors depends on the chosen mobility model: in this work, we choose the HRW model because it is constructed upon real mobility traces, thus providing the opportunity to better understand the impact that the use of RLNC techniques can have in urban areas.

7. CONCLUSIONS

In this paper, we investigated the use of RLNC techniques over LMS satellite channels to extend the satellite coverage in urban areas. Mobile nodes can effectively cooperate by relying on RLNC-based gossiping algorithms, removing the need for any fixed equipment on the ground. We have provided an analytical model that takes into account the average number of neighbor nodes $<d>$ on the ground and the number of gossiped symbols per mobile node, in order to understand how effective the cooperation among mobile nodes can be. Furthermore, we discussed the advantages brought by the use of the recoding feature that RLNC techniques can provide, showing how it can critical to reduce the collision rate in the VANET, while still guaranteeing full coverage.

A mobility model built upon real traces has been used in the simulator, in order to provide numerical results as realistic as possible. The results show that RLNC-based gossiping can efficiently complement the satellite signal in ensuring a large coverage probability in urban areas, where cluster of vehicles can exchange M2M data coming from a remote source. Several parameters can be finely tuned, in order to adapt the proposed setup to different conditions, such as severely impaired communication channels, varying number of neighbors, and the size of the RLNC generation. Eventually, we have empirically shown the relationship between the average number of neighbors and the generation size, highlighting the impact of the ratio $k\,/{<d>}$ on the coverage probability.

ACKNOWLEDGEMENT

This work contains the outcomes of a study carried out within the Network Coding Applications in Satellite Communication Networks working group, part of the Satellite Network of Excellence (SatNEx) IV, phase I, funded by the European Space Agency.

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