Understanding spurious message forwarding in VANET beacon-less dissemination protocols: an analytical approach

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Abstract—Message dissemination is a key component of Vehicular Ad hoc Networks (VANETs). It enables the capability of Intelligent Transportation Systems to support safety and infotainment services for vehicles and people on travel. Dissemination in VANETs typically relies on the intelligent election of selected vehicles to act as relay nodes, a critical element that serves to avoid broadcasting storm issues. This paper presents an analytical model for evaluating the performance of a class of distributed, beacon-less, dissemination protocols in a linear VANET (e.g., a highway). NS-2 based simulations are employed to validate the model. The results are used to gain insight into the spurious forwarding problem, which accompanies the use of timer-based VANET networking protocols. We characterize the impact of this phenomenon on the achievable level of the system's broadcast throughput capacity rate. Resolution approaches are proposed and analyzed.

Index Terms—VANET, dissemination, cross layer protocol interaction, message forwarding.

I. Introduction

THERE is a vastly increasing interest in the design, experimentation and implementation of Vehicular Ad hoc NETworks (VANETs), as outlined in recent surveys, e.g., [1] [2] [3] [4] [5]. The initial growth has been primarily boosted by safety requirements, yet it has soon been recognized that such systems offer promise for reducing cost, message delays and polluting processes caused by road traffic overloads. They are essential for the provision of information and comfort services to persons while traveling. In addition to cellular platforms, such as LTE [6], VANET systems are expected to be implemented as core modules that are used to support vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication network systems for the provision of Intelligent Transportation System services (e.g., see [7]).

Key to the support of safety and infotainment applications is the availability of mechanisms for an efficient distribution of information among vehicles based on *dissemination protocols.* A disseminated message flow may start at an information source that resides at a Road Side Unit (RSU), fed by a remote server, or at an On-Board Unit (OBU), residing in a vehicle

that has useful information of interest to other roaming users. Inherent to the dissemination process is the use of intelligent and adaptive broadcasting algorithms that make efficient use of vehicular communications networking resources, avoiding the so called broadcast storm problem [8]. Over the last decade, an important body of literature has grown around the development and study of VANET routing and dissemination protocols (e.g., see the surveys presented in [9] [10] [11] [12] [13]).

The main approaches used for implementing dissemination protocols have been classified as probabilistic and delay (or timer) based [9] [11]. In [11], network coding algorithms have been identified as forming such a third class of schemes. A key operational element involves the use of beacon messages (sometimes referred to as "hello" messages). Beacon based dissemination protocols assume that vehicles are informed as to the relevant state of their neighborhood (including, for example, the positions and speeds of close-by vehicles) through the timely distribution of beacon messages. This side information is also used by a vehicular networking entity to decide whether to relay a new message that it receives, and determine the targeted destination vehicles. Beacon-less protocols are based on the employment of autonomous logic. Decisions as to whether to forward a message or not are then taken at the reception of each new message, based solely on the embedded protocol logic and on control information that is contained in the message itself. In this work, we address this last category of dissemination protocols.

Beacon-less dissemination protocols use either probabilistic or timer-based algorithms. In the first case, the decision whether to forward a message is based on the outcome presented by the realization of a random variable, whose distribution may depend on the (relative) positions of the sending and receiving vehicles (e.g., see [14] [15]).

The principle of timer-based protocols is that the selected forwarding vehicle is the one setting the shortest timer among all of those vehicles that have received a broadcasted message. One of most popular forwarding protocol, referred here to as Distance Based Forwarding (DBF), was described in [16], [17] and [18]. The core idea is to elect the forwarding vehicle to be the one that is most distant from the vehicle V that has broadcasted the message. Involved in this selection process are all vehicles that have received the message from V. Each such vehicle triggers the activation of a timeout timer whose timeout level is set to a value that is a decreasing function of the vehicle's distance from V. A number of other variants of

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timer-based dissemination protocols have also been proposed [19] [20] [21] [22].

Ideally, a dissemination logic should identify, in a given area, a single vehicle in charge of forwarding the message, so as to minimize the number of copies of the same message that are received by each vehicle [23]. As a result, within the area delimited by a link's radio transmission range, at any given time, a single forwarding action should be undertaken. Forwarding of a message by multiple close-by vehicles will generally lead to performance degradation. As the rate of the message flow that is to be disseminated increases, duplicated forwarding actions, if not suppressed, lead to congestion at the radio interface and to early performance collapse.

In practice, mechanisms used by beacon-less protocols cannot completely avoid the occurrence of duplicated message transmissions. As discussed in [18], duplicate forwarding is induced by two key sources: i) spurious emissions that can be avoided by canceling a message waiting for forwarding, if a duplicate is received while the timer is running (we refer to this kind of suppression as *inhibition*); ii) spurious emissions that occur during the time interval required for the lower protocol layers to complete the delivery of a message that has been the first one to be selected for forwarding. Operating under a specific implementation of lower layer protocols, this last source of spurious emissions cannot generally be avoided. The ordered message forwarding structure that dissemination protocols strive to achieve can be violated by spurious forwarding occurrences, particularly as the offered message rate increases. It is therefore essential to characterize the features of the spurious forwarding phenomena.

In this paper, we aim to carry out quantitative analysis that serves to model the spurious forwarding issue. Our contributions are:

1) we provide a mathematical model that is used to calculate and evaluate key performance metrics that convey the impact of the spurious forwarding phenomena on the system's throughput performance behavior;
2) we validate the proposed model via Monte Carlo simulations involving vehicular flows along a highway;
3) we provide for the proper selection of dissemination protocol parameters.

As for the third contribution, we provide a lower bound on the spacing time period τ_{RSU} that should be set for messages transmitted by the RSU onto the highway. Through such a flow control regulation, it is possible to mitigate the negative impact of spurious forwarding phenomena on the performance of the VANET system. The time period τ_{RSU} should be no shorter than the derived statistical bound on the time that is taken by a message to traverse two hops in along the chain of relay nodes spanning the highway. The calculation of this bound is performed through the use of the system model developed in this work. We also provide guidelines for the setting of the maximum range to be configured for a single hop, serving to control the radio channel impact on the performance effectiveness of the dissemination process.

In the rest of the paper, we lay out the basic principles of beacon-less dissemination protocols to highlight the issue of spurious forwarding and its causes (Section II). An analytical model of spurious forwarding is presented in Section III and validated via simulations in Section IV. In Section V we use the model to provide an approach to the design of beacon-less dissemination protocols by dimensioning the timer value range. The dimensioning approach maintains the simplicity of the protocol while achieving a stable high throughput rate. Maximum hop range dimensioning is discussed in Section VI, where we also motivate the selection of the adopted path loss model. A discussion of the relevance of the proposed model is carried out in Section VII. Final remarks are given in Section VIII.

II. PRINCIPLES OF BEACON-LESS DISSEMINATION PROTOCOLS

We consider a VANET based service under which information messages are sent in a push mode to all vehicles that travel within a specified range (corresponding to the underlying Region Of Interest, ROI) from a source node that produces and disseminates these messages. Direct reception of message transmissions executed by the source node is attained at vehicles that reside within a limited distance from the source node; this range is typically of the order of one (to several) hundred meters. To disseminate the messages over a wider area, multi-hop vehicle-to-vehicle (V2V) communications networking methods must be exploited. To avoid message transport degradations that are induced by broadcast storm phenomena, effective dissemination protocols act to select a proper subset of vehicular nodes that travel in the ROI to act as Relay Nodes (RN). Only RNs forward copies of the message to be disseminated. The performance efficiency of the dissemination process is critically dependent upon the effectiveness of the mechanism employed in selecting vehicles to act as RNs. It is often preferred to implement a distributed and beacon-less RN selection mechanism, as is assumed in this paper. The relaying protocol can be executed by the network layer entities embedded in the OBU/RSU modules, as performed for the recently standardized ETSI GeoNetworking protocol implementation [24]. In the following we refer to messages when dealing with application/network layers and frames in case of MAC/PHY layers, one message being carried by a single frame.

Under the class of distributed RN election algorithms, the following process is undertaken. Assume node (i.e., vehicle) A to transmit a new message. Every node that directly (i.e., over the underlying communications link) successfully receives this message regards itself as a potential RN. If elected, the node will forward the message to other vehicles traveling along the road. Otherwise, the node will drop the message. To avoid ineffective contentions among RNs that are located close to each, it is essential to aim the selection of RNs to be such that they are located at proper ranges from each other. If two RNs reside in very close proximity and they both elect themselves as relays, then their transmissions may either collide (i.e., interfere with each other) or would not serve to achieve productive progress in extending the dissemination coverage, as their transmissions would cover essentially the same spatial regions. In addition, two elected RNs must be
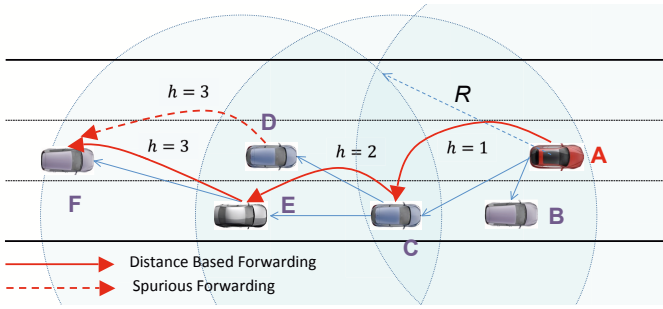
Fig. 1. An example of message forwarding: the desired sequence of forwarding vehicles is $A - C - E$. The emission of a message copy on behalf of D is a spurious forwarding.
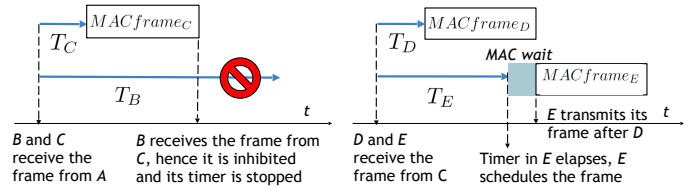

Fig. 2. Illustrative inhibition and spurious forwarding. T_X denotes the timer value set by node X. Case (a): nodes B and C receive the frame transmitted by A (see Figure 1), T_C elapses first so that C transmits the frame before B does, hence B is inhibited. Case (b): nodes D and E receive the frame transmitted by C (see Figure 1), T_D elapses first and D transmits its frame; however, prior to the completion of this transmission, T_E elapses, inducing E to instruct its MAC entity to carry out the transmission of the frame (spurious forwarding).

located within communications range to assure successful reception of relayed messages. The proper ranges depend on the prescribed values of the transmission rates and on the targeted bit error rate level. Under such constraints, it is generally desirable to realize a relay configuration layout that uses a minimum number of RNs, while assuring the dissemination of messages over the ROI. As a matter of example, with reference to Figure 1, consider a message that is transmitted by vehicle A. Vehicles B and C are shown to directly receive this message. Since the respective coverage areas attained by B and C almost completely overlap, it is not effective to task both vehicles to acts as RNs. Vehicle C is shown to elect itself as the RN for this message. For the same reason, in considering the setting of the third hop, the further away vehicle E elects itself to serve as the RN.

Under an ideal implementation of the dissemination protocol, each vehicle (traveling along a linear road) should receive a given message no more then twice; i.e., from its closest neighboring RNs that are located, in reference to the source node, at its upstream and downstream directions. The generation and reception of an excess number of message copies are associated with *spurious forwarding*. Such spuriously forwarded messages[1] tend to increase overhead and system traffic load.

Two basic approaches are generally used to suppress the occurrence of spuriously forwarded message transmissions:

1) *probabilistic dissemination*: a node receiving a new message forwards it with probability $q < 1$; the probability value might depend on the location of the sending and receiving nodes.

2) *timer-based dissemination*: a node receiving a new message sets a timer to delay the forwarding of the message; the message is forwarded upon the expiration of the timer; the forwarding of the scheduled message will be canceled if a second copy of the message is received prior to the expiration of the timer (*inhibition rule*).

The implementation of the inhibition rule requires a delayed based trigger of the forwarding action. The use of timer-based forwarding rule can in principle suppress the creation of message duplicates, since the vehicle that has set the lowest timer value will be the one that will act first to forward

the message, causing other neighboring vehicles to cancel their plans to forward the same message. For example, in considering the scenario shown in Figure 1, assume the timer activated by node C to expire before the expiration of the timer activated by node B. Upon the receipt by node B of the message forwarded by node C, node B will cancel its own forwarding action (see Figure 2).

We note that the suppression of a spurious forwarding event would fail when the reception of the second copy of a given message (the one that triggers inhibition) either fails or is detected only after the receiving node has already sent its copy of the message. The latter outcome is possible since in general it takes some (non-null) time to transport a message between vehicles. With reference to Figure 2, we note that during the time that it takes to complete the delivery of the message sent by node E, nearby nodes C, D and F are not aware of this forwarding action. The duration of such a "blind" period, depends on the characteristics of the radio link and of the mechanism used for implementing protocol execution process.

To illustrate, assume the dissemination logic to be implemented as a network layer protocol. Both nodes D and E of Figure 1 decide to schedule the forwarding of the message received from C. If the forwarding timers excited by these two nodes are triggered at instants of time whose difference is lower than the MAC frame delivery time latency (see Figure 2), both nodes will proceed with the forwarding of their copies of the same message. It is noted that such a duplicate action cannot be avoided as once the network layer entity has passed the message to its MAC layer entity, the latter is committed to attempt to execute its transmission task. The network layer entity residing at a node cannot cancel its direction to its MAC layer entity at a later time (e.g., once it has realized that a copy of the same message has been transmitted by another vehicle).

In the rest of this work, we envision the definition of the dissemination protocol logic as a module inside the network layer, thus residing on top of the link/MAC layer; this choice provides flexibility to evolve the radio access layer and the routing logic independently of each other. Moreover, it is consistent with ETSI standards [25].

III. MODEL OF A LINEAR VANET

The following hypotheses are made:

[1]In [18], they are referred to as duplicated messages.

1) *Vehicle equipment*: We assume each vehicle to be equipped with an OBU that contains the employed networking module, a GPS module to monitor its position and the IEEE802.11p radio equipments;

2) *Linear road*: the considered service area consists of a linear road (highway). Message flows originate at a single RSU station and are targeted for dissemination to all vehicles that travel along the road. The width of the road is neglected in our analysis, noting that the ratio of the width to the link communications range is low. Hence, the position of a node is represented by a single coordinate. The RSU is assumed to be located at $x = 0$.

3) *Spatial distribution of vehicles*: vehicles are distributed along the road in accordance with a spatial Poisson point process[2] with rate parameter λ [vehicles/meter].

4) *Radio coverage*: a transmitted frame is assumed to be correctly received if the Signal-to-Interference-plus-Noise Ratio (SINR) at the receiver (at reception time) is higher than a given threshold level; the setting of the latter depends on the employed modulation/coding scheme and on the prescribed target MAC layer bit-error-rate. The details of the physical channel model are discussed in subsection III-A and further in Section VI.

5) *Vehicular mobility*: the targeted time scale for sending successive messages that belong to a broadcasted flow is much shorter than the underlying vehicular mobility time scale. Hence, as it relates to our communications networking model, vehicles can be considered to effectively be stationary.

We have used simulation runs to validate our models. In these simulations, we have relaxed hypotheses 2), 3), and 5). We have included in our simulations realistic vehicular multi-lane highway mobility models. These models have been used to characterize the distribution of vehicular spatial positions; they include effects induced by inter-relationships involving spacings among moving vehicles. Using these results, we have confirmed the acceptability of the simplifications introduced in the definition of our analytical models.

We start our analysis by specifying the models used to describe the operation of the involved PHY and MAC layer processes (subsections III-A and III-B, respectively). Then, assuming low message rates, as often done for such systems, e.g., when aiming to transport safety oriented message flows at low end-to-end message latency levels, we proceed to carry out the analyses of two representative message forwarding protocols: the DBF protocol in subsection III-D and the TBN protocol in subsection III-E.

A. Physical layer model

We use a basic commonly employed deterministic propagation model[3], prescribing a path gain that depends on the

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[2] Poisson spatial distribution of vehicles is deemed to be appropriate under free flow conditions. It can also be considered a good model for the characterization of vehicular positions along a multi-lane road, noting that then the spacings between vehicles are characterized by the interval statistics of the super-imposed point process.

[3] The impact of the path gain level on the dissemination process is further discussed in Section VI

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distance between a transmitter and its intended receiver. We set $P_{rx} = G(d)P_{tx}$, where $G(d)$ is the path gain at distance $d > 0$ from the transmitter. For numerical evaluations, we select a corresponding model that is derived from highway measurements [26]. It represents the gain as a two exponent based power-low function:

$$G(d) = \begin{cases} \kappa \left(\dfrac{d_0}{d}\right)^2 & d_0 \leq d \leq d_1 \\[2ex] \kappa \left(\dfrac{d_0}{d_1}\right)^2 \left(\dfrac{d_1}{d}\right)^{\alpha_1} & d_1 \leq d \leq d_2 \\[2ex] \kappa \left(\dfrac{d_0}{d_1}\right)^2 \left(\dfrac{d_1}{d_2}\right)^{\alpha_1} \left(\dfrac{d_2}{d}\right)^{\alpha_2} & d \geq d_2 \end{cases}$$

(1)

Typical suggested values for the two exponents are $\alpha_1 = 2.0763$ and $\alpha_2 = 3.9369$, with $d_0 = 1\ m$, $d_1 = 40\ m$ and $d_2 = 120\ m$. We also set $\kappa = 2.983 \cdot 10^{-5}$ or $-45.25\ dB$. We assume a carrier frequency of $f_c = 5900\ MHz$. These are illustrative values; our analytical methods are also applicable when using other scenario and system parameters.

As for the communication link model, we assume the interference and noise signals to be modeled as Gaussian processes. Accordingly, we use an Additive White Gaussian Noise type channel model, and consequently employ Shannon's channel capacity formula. The link capacity C_L is thus calculated as $C_L = W \log_2(1 + SINR/\Gamma)$, where W is the channel's bandwidth, $SINR$ is the signal to interference plus noise ratio monitored at the receiver and Γ is a gap factor[4]. We calculate the $SINR$ level monitored at a receiver as: $SINR = G(d)P_{tx}/(P_N + P_I)$, where P_I denotes the multi-user interference power, and $P_N = N_0 W$ is the thermal noise power. The noise power spectral density level is assumed to be set to $N_0 = -174\ dBm/Hz$. As conventionally assumed for low message rate operation, we set $P_I = 0$; we consequently denote in the following $SINR$ as SNR. As prescribed by the Dedicated Short Range Communication (DSRC) standard, the channel bandwidth is set equal to $W = 10\ MHz$.

The receiving device is said to perform correct message decoding when the air bit rate F_A across the link is lower than the link's capacity; i.e., $F_A \leq C_L$ or $SNR = G(d)P_{tx}/(N_0 W) \geq \Gamma(2^{F_A/W} - 1) \equiv \gamma_{th}$. Given the path gain model expressed by eq. (1), the condition $SNR \geq \gamma_{th}$ is equivalent to the requirement $d \leq R_{th}$, with R_{th} representing the unique under which $G(R_{th})P_{tx}/(N_0 W) = \gamma_{th}$. Henceforth, we assume that when operating at the configured air bit rate, correct reception of a message sent across a link is achieved when the covered range is lower than the calculated range span R_{th}.

Table I presents illustrative values for the γ_{th} levels that are required to achieve the air bit rates specified by the IEEE 802.11p recommendation, for three values of the transmit power level P_{tx}. The gap factor is set to $\Gamma = 11.74$, corresponding to a symbol error probability of 10^{-5}. Table I also lists the effective link range coverage R_{th} values that are attained under the specified air bit rate and power levels.

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[4] For M-QAM constellations, we set $\Gamma = 2/3 \log_2(2/P_e)$, where P_e is the targeted symbol error probability.

TABLE I
REQUIRED SIGNAL-TO-NOISE RATIO LEVELS γ_{th} AND LINK RANGES R_{th} FOR ACHIEVING THE AIR BIT RATES F_A SPECIFIED BY IEEE 802.11P, UNDER THE PATH LOSS MODEL OF EQ. (1).

F_A [Mbps]	γ_{th} [dB]	R_{th} [m] (500 mW)	R_{th} [m] (200 mW)	R_{th} [m] (100 mW)
3	3.16	983	782	657
4.5	4.30	911	724	609
6	6.31	827	658	553
9	10.17	734	584	491
12	15.23	664	528	444
18	29.14	564	449	377
24	50.22	492	391	329
27	64.55	462	368	309

TABLE II
MAIN PARAMETER VALUES FOR THE MAC PROTOCOL OF IEEE 802.11P.

Symbol	Description	Value
W_0	base contention window	16
σ	count down slot time	13 μs
DIFS	DCF Inter-Frame Spacing	58 μs
L	frame payload size	1000 $bytes$
H_{MAC}	MAC overhead	28 $bytes$
H_{PHY}	PHY overhead	136 $bits$
F_A	air bit rate	3, 4.5, 6, 9, 12, 18, 24, 27 $Mbps$
C_{br}	basic bit rate	3 $Mbps$

B. MAC layer model

The MAC layer considered here follows that specified by the IEEE 802.11p standard. It is based on a version of the CSMA/CA protocol. We consider only broadcast frames, so that no acknowledgement frames (ACKs) are used. The contention window size is set at a constant value of W_0, and each frame is transmitted only once.

When it has a frame to send, a node waits for an idle time duration that is equal to the Distributed Coordination Function (DCF) Inter-Frame Spacing (DIFS) value. It then sets a countdown counter whose duration is drawn from a uniform distribution over the integer set $\{0, \ldots, W_0-1\}$, and then waits for that number of idle slots; each slot is of duration σ. When the counter (which counts down when idle slots are detected) reaches the 0 value, the frame is transmitted. The transmission time of a MAC frame is equal to $\tau_{tx} = \tau_{oh} + L/F_A$, where τ_{oh} is the time taken for the transmission of the embedded MAC and PHY overhead symbols and preambles, L is the frame payload size (assumed hereby to be the same for all frames) and F_A is the air bit rate.

The values of the parameters, based on a typical configuration used for IEEE 802.11p, are reported in Table II. The frame overhead transmission time is equal to $\tau_{oh} = H_{PHY}/C_{br} + H_{MAC}/F_A$, where C_{br} is the basic bit rate. For $F_A = 6\ Mbps$ and $C_{br} = 3\ Mbps$, we obtain $\tau_{oh} = 82.7\ \mu s$. Consequently, we obtain $\tau_{tx} = 1.416\ ms$, assuming $L = 1000\ bytes$.

C. Timer setting

The forwarding timer is set to a value that lies in the range $[T_{min}, T_{max}]$. The dimensioning criteria employed in setting the timer's maximum and minimum values are derived and presented in Section V. We consider two examples of timer-based message dissemination protocols, referred to as
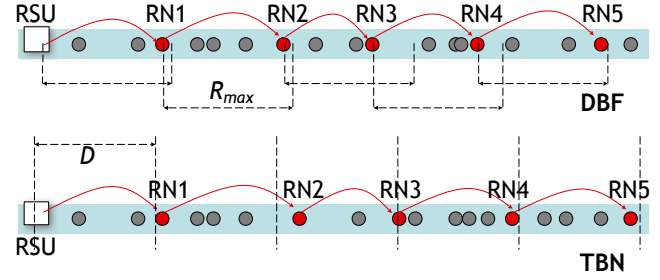

Fig. 3. Examples of message disseminations under different protocols. The circle associated to RNk denotes the k-th relay nodes. DBF (top picture): relay node is selected at each hop as the node within the coverage range that is located farthest away from the previous relay node; TBN (bottom picture): relay node is selected at each hop as the node that is closest to the nominal position; such positions are spaced out evenly at distance D along the highway.

Distance Based Forwarding (DBF) [16] [17] [18] and Timer-based Backbone Network (TBN) [27]. The DBF and TBN protocols are representatives of two key classes of forwarding schemes. Under the first class of protocols, the scheme strives to have each forwarded message cover the longest possible "jump" while transported over a single hop to a subsequent node that will serve to relay it over the next hop. The scheme devised under the second class of protocols sets the range of each hop to a preferential value, aiming the reception and relaying of a forwarded message to be performed by a node that is located at a position along the highway that is as close as possible to a preferential location.

In modeling the DBF protocol, we set the timer value of a node A that is receiving a message from a transmitting node S to be equal to $T = T_{min} + (T_{max} - T_{min})(1 - d_{AS}/R_{max})$, provided that $d_{AS} \leq R_{max}$, where R_{max} is defined to be the *maximum hop range* and d_{AS} is the distance between nodes S and A. If $d_{AS} > R_{max}$, vehicle A does not take part in the dissemination process for that hop. Thus, only vehicles that are located within a distance R_{max} of the source vehicle S are eligible for acting as relay nodes. The dimensioning of R_{max} is discussed in Section VI.

Under the TBN forwarding protocol, a target value is set for the distance between consecutive forwarding nodes. This level is denoted as D. The value of D can be dimensioned according to the link budget so as to maximize the broadcast throughput of the VANET [28]. To ensure feasibility, D must be no greater than half of the VANET radio equipment's transmission range. The desired nominal locations of the relay nodes that are situated along the road are $P_k, k \in \mathbb{Z}$, with $d_{P_k P_{k+1}} = D$. Let $k(A) = \arg\min_{k \in \mathbb{Z}} d_{P_k, A}$. The timer is set to $T = T_{min} + (T_{max} - T_{min})2d_{P_{k(A)}, A}/D$. Note that $d_{P_{k(A)}, A} \leq D/2$, since $k(A)$ is the index of the nominal forwarding location closest to A.

In Figure 3, we present examples of message dissemination flows that are realized in accordance with the DBF and TBN schemes. Arrows connect successive relay nodes, labeled as RN_k. In the figure, we assume the system to implement a maximum hop range R_{max}, set equal to the radio coverage distance R_{th}.

D. Forwarding model under the DBF protocol

Consider a generic relay node A located at $x = x_0$ that forwards a message at time $t = t_0$; i.e., the timer has expired and a message is then passed down to the MAC layer for transmission. The signal transmitted by A is received and correctly decoded by receivers located within a distance R_{th} from the position of A. According to the protocol rules stated in Section III-C, only vehicles within range R_{max} of A are involved in the forwarding process. Hence, the road section covered by the forwarding action of A spans the range $R \equiv \min\{R_{max}, R_{th}\}$. The dimensioning of R_{max} is discussed in Section VI, where it is argued that it is advisable to set $R_{max} < R_{th}$.

Provided that there is at least one other node in $(x_0, x_0 + R]$, the position of the most distant next-hop node is at a range $Y = R - V$ from A, where V is a "residual life" type random variable associated with the inter-nodal distance. Since vehicles are spatially located in accordance with a Poisson process, the random variable $\hat{V} = V/R$ is governed by the following Probability Density Function (PDF)[5]:

$$f_{\hat{V}}(v) = \frac{be^{-bv}}{1 - e^{-b}}, \quad v \in [0, 1]$$

with $b = \lambda R$. Consequently, the average distance between A and the next forwarding node is given as:

$$\mathrm{E}[Y] = R(1 - \mathrm{E}[\hat{V}]) = R\left(\frac{1}{1 - e^{-b}} - \frac{1}{b}\right)$$

According to the DBF timer equation stated in subsection III-C, a node at distance x from A that has received a message from A, sets its timer value to be equal to

$$
\begin{aligned}
T \equiv T(x) &= T_{min} + (T_{max} - T_{min})(1 - x/R_{max}) \\
&= T'_{min} + (T_{max} - T'_{min})(1 - x/R)
\end{aligned}
$$

with $T'_{min} = T_{min}(R/R_{max}) + T_{max}(1 - R/R_{max})$.

Let B be the node in $(x_0, x_0 + R]$ that is located farthest away from A, i.e., at a distance $Y = R(1 - \hat{V})$ from A. Its timer is set at: $T_B = T'_{min} + (T_{max} - T'_{min})(1 - Y/R) = T'_{min} + (T_{max} - T'_{min})\hat{V}$. We define a normalized timer level $\hat{T}$ as $\hat{T} \equiv (T - T'_{min})/(T_{max} - T'_{min})$. Then, $\hat{T}_B = \hat{V}$, so that the PDF of the normalized timer is the same as that of $\hat{V}$, namely $f_{\hat{T}_B}(t) = be^{-bt}/(1 - e^{-b})$ for $t \in [0, 1]$.

To calculate the probability of spurious forwarding, we set Θ to denote the MAC delay; i.e., the time required for the MAC layer to send out the MAC frame carrying a message received from the network layer entity[6]. If the network layer entity of A sends the message to its MAC entity at time t_0, the corresponding frame transmission process across the physical link will be completed at time $t_0 + \Theta$ (see Figure 4). Nodes located close to A whose timers expire later than that of A, will not learn about the frame sent by A until time $t_0 + \Theta$. If during the time interval $(t_0, t_0 + \Theta]$ their timers expire,

their network layer entities will also proceed to pass their copies of the same message to their respective MAC layer entities. Consequently, they will end up transmitting the same copy of the message as that forwarded by node A. Such nodes are identified as spurious forwarders. Those nodes that have scheduled the forwarding of the same message and whose timers expire after time $t_0 + \Theta$, will be able to detect the transmission of the same message by another node prior to the expiration of their own timer, and will thus be inhibited.

To be a spurious forwarder with respect to A, given the MAC delay Θ_A at A, a node S must be located within a distance Δx of A such that $\Delta T = (T_{max} - T_{min})\Delta x/R \leq \Theta_A$, i.e., $\Delta x \leq R\Theta_A/(T_{max} - T_{min})')$. Since nodes are distributed according to a Poisson spatial process, the probability Q_n that there are $N = n$ such spurious forwarders is given as:

$$Q_n = \frac{\left(\frac{\lambda R\Theta_A}{(T_{max} - T'_{min})}\right)^n}{n!} e^{-\frac{\lambda R\Theta_A}{(T_{max} - T'_{min})}}, \quad n \geq 0 \quad (2)$$

The value of Θ_A can be calculated as follows. The time required to transmit the backlog associated with the existence of N spurious forwarders is equal to $N\tau_{MAC} + \sigma S_N$ for $N \geq 0$, where S_N is the overall number of empty MAC mini-slots of duration σ used by the N nodes to transmit their MAC frames and $\tau_{MAC} = \tau_{tx} + DIFS + \sigma$, with τ_{tx} as defined in subsection III-B. The number of idle mini-slots is expressed as $S_N = \max\{U_1, \ldots, U_N\}$, for $N \geq 1$, and $S_N = 0$ for $N = 0$; where U_j denotes a discrete random variable that follows a uniform distribution over $[0, W_0 - 1]$.

As an approximation, we replace the random variable S_N with its mean value, when conditioning on $N = n$. We readily obtain the following:

$$\mu_n \equiv \mathrm{E}[S_N | N = n] = W_0 - \sum_{j=1}^{W_0} \left(\frac{j}{W_0}\right)^n, \qquad n \geq 0$$

We next consider the MAC delay Θ_B incurred at node B (see Figure 4). Θ_B reduces to the MAC and physical layer
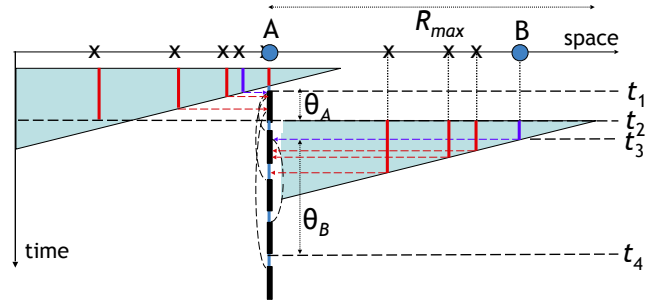

Fig. 4. Example for the evaluation of the MAC delay in a chain of forwarding vehicles. The triangle shows the profile of the timer function as a function of the spatial coordinate. Timer levels set by nodes along the highway are represented by vertical segments inside the triangle. The shortest timer express at node A at time t_1. Then, A commits its MAC layer to sending a frame with the message. Transmission of A is completed at time t_2, thus inhibiting the third node on its left. Yet, the two closest nodes on the left of A have already committed MAC entities to sending their frames, since their timer have expired before t_2. Node B receives the frame from A at time t_2 and starts its timer. At time t_3 it is ready to send its frame, but it has to contend the channel with the two spurious forwarding nodes on the left of A. At time t_4 B manages to send its frame, thus incurring in a MAC delay θ_B.

---

[5]The variable $\hat{V}$ is conditional on there being at least one vehicle in $(x_0, x_0 + R]$. For practical values of vehicular density and radio coverage range, that event assumes a probability $\simeq 1$.

[6]The MAC delay includes the time required for the MAC and PHY layers to execute back off and to carry out MAC frame processing and transmission plus waiting time at MAC layer, depending on the wireless channel load.

fixed time τ_{MAC} in case the spurious forwarders triggered by A are already done when B is ready to send its frame. If instead there is still backlog to be cleared in the MAC layer, due to the spurious forwarders of A, node B enters a competition with those nodes, according to the CSMA/CA rules. Then, the MAC delay incurred by node B includes a component depending on that contention.

Formally, the random variable Θ_B, conditioned on the joint event $\{N = n, T_B = t\}$, is expressed as:

$$\Theta_B|_{\{n,t\}} = \tau_{MAC}$$

for $n\tau_{MAC} + \mu_n\sigma \leq t$ and

$$\Theta_B|_{\{n,t\}} = \tau_{MAC} + \sigma U_B + Z(n\tau_{MAC} + \mu_n\sigma - t)$$

for $n\tau_{MAC} + \mu_n\sigma > t$, where U_B is a discrete uniform random variable over $[0, W_0 - 1]$ and Z is a uniform random variable over $[0, 1]$. The variable Z accounts for the random scheduling latency realized by the IEEE 802.11p DCF, so that node B has to wait a random portion of the residual time needed to clear the spurious forwarders backlog.

Let $n(v)$ be the least integer such that $n\tau_{MAC} + \mu_n\sigma > T'_{min} + (T_{max} - T'_{min})v$ for $v \in (0, 1)$. Then

$$\mathrm{E}[\Theta_B|T_B = T'_{min} + (T_{max} - T'_{min})v] = \mathrm{E}[\Theta_B|\hat{V} = v] =$$
$$= \tau_{MAC} + \frac{W_0 - 1}{2}\sigma \sum_{n=n(v)}^{\infty} Q_n + \frac{1}{2}\sum_{n=n(v)}^{\infty} Q_n g_n(v) \quad (3)$$

where $g_n(v) \equiv n\tau_{MAC} + \mu_n\sigma - T'_{min} - (T_{max} - T'_{min})v$. Finally, we obtain the average value of Θ_B by removing the conditioning on $\hat{V}$:

$$\mathrm{E}[\Theta_B] = \int_0^1 \mathrm{E}[\Theta_B|\hat{V} = v]\frac{be^{-bv}}{1 - e^{-b}}\, dv \quad (4)$$

The value of $\mathrm{E}[\Theta_B]$ is calculated by: i) assuming stationarity along the highway, so that $\Theta_A \sim \Theta_B \sim \Theta$; ii) replacing the quantity Θ_A in eq. (2) by its mean value $\mathrm{E}[\Theta_A] = \mathrm{E}[\Theta_B]$. This yields a fixed point equation, based on the system of non linear eqs. (2), (3) and (4). For the numerical values of interest, we have found the iterative numerical process that solves for the root to converge extremely fast.

The probability of spurious forwarding is next obtained by calculating the probability that at least one node resides in an interval of length $\Delta x = R\mathrm{E}[\Theta]/(T_{max} - T'_{min})$ that immediately precedes the designated forwarding node. It is then given as:

$$P_{sf} = 1 - e^{-\lambda R\mathrm{E}[\Theta]/(T_{max} - T'_{min})} = 1 - e^{-\mathrm{E}[N]}$$

Note that the mean number of spurious forwarders is $\mathrm{E}[N] = \lambda R\mathrm{E}[\Theta]/(T_{max} - T'_{min})$, as obtained from eq.(2).

E. Forwarding model under the TBN protocol

Under the TBN scheme, the mean forwarding interval length is $\mathrm{E}[Y] = D$. The timer value is set as $T = T_{min} + (T_{max} - T_{min})2|X|/D$, where $X \in [-D/2, D/2]$ is the displacement between the candidate forwarding node and the center of the forwarding interval of length D. Accounting for the Poisson vehicular spatial distribution and the symmetry of the timer

TABLE III
SIMULATIONS PARAMETERS VALUES.

Parameters	Values
Offered message rate $(1/\tau_{RSU})$	$1\ msg/s$
message size (L)	$1000\ bytes$
D	$500\ m$
T_{max}	$100\ ms,\ 200\ ms$
T_{min}	0
$R_{th} = R_{max} = R$	$827\ m$
Propagation Model	Two ray ground $(\alpha_1 = 2, \alpha_2 = 4)$
Carrier frequency	$5.9\ GHz$
Transmission Power	$500\ mW$
Air Bit Rate (F_A)	$6\ Mbps$
Noise Floor	$-104\ dBm$
Road length (2ℓ)	$10\ km$
Number of lanes	6
Traffic density (λ)	$20, 30, 40, 50, 60\ veh/km$
Mean target velocity (v_{mean})	$90, 110, 130\ km/h$

function, the PDF of the displacement X (conditional on there being at least one vehicle in the forwarding interval of length D) is expressed as

$$f_X(x) = \frac{\lambda e^{-2\lambda|x|}}{1 - e^{-\lambda D}}, \qquad -\frac{D}{2} \leq x \leq \frac{D}{2}$$

The normalized timer duration $\hat{T} = (T - T_{min})/(T_{max} - T_{min})$ is equal to the normalized distance from the nominal position, i.e., $\hat{T} = 2|X|/D$. Hence, $f_{\hat{T}}(v) = ae^{-at}/(1 - e^{-a})$ for $t \in [0, 1]$, with $a = \lambda D$. The mean value of the timer is then obtained to be equal to $\mathrm{E}[\hat{T}] = 1/a - 1/(e^a - 1)$.

The spurious forwarding phenomenon can be analyzed by invoking a model that is similar to that presented in Section III-D, except that we now replace everywhere parameter $b = \lambda R$ with $a = \lambda D$, and $\hat{V}$ with $\hat{T}$. Hence, the spurious forwarding probability is equal to $P_{sf} = 1 - e^{-a\mathrm{E}[\Theta]/(T_{max} - T_{min})}$, and the average number of spurious forwarders is given as $\mathrm{E}[N] = a\mathrm{E}[\Theta]/(T_{max} - T_{min})$.

IV. MODEL VALIDATION

We have carried out simulations of a linear multi-lane highway to assess the accuracy of the analytical model derived in Section III. For this purpose, we have configured the simulation system to employ two main building blocks: a micro-mobility simulator, which models vehicular mobility, and the communication process simulator. Patterns of mobility of vehicles along the highway are generated by the micro-mobility simulator by assigning vehicles target velocity according to a truncated Gaussian PDF and by using the well known car-following model. This method is used by most current vehicular micro-mobility simulators, such as SUMO [29]. The communication process is simulated by using the NS-2 simulator.

Performance evaluation results have been obtained by performing 100 simulation repetitions for every scenario under consideration, whereby each simulation scenario was run for a period of $45\ sec$. The numerical values that were used to configure the simulation parameters are listed in Table III.

We consider a linear road of $10\ km$ length with three lanes in each direction, with the RSU node located at the middle of the road. A Poisson flow of vehicles is injected into each lane

from the road borders. The intensity of the vehicular flow is tuned so that the overall average vehicular density along the road equals the desired value of λ at equilibrium.

For each injected vehicle, a speed value v is extracted according to a Gaussian PDF with mean v_{mean} and standard deviation $0.1 \cdot v_{mean}$. The extracted value is clipped on the upper side to a value that is determined by the maximum admissible speed value, $v_{max} = 150 \ km/h$. On the lower side, the speed value is truncated to a minimum value set equal to $0.5 \cdot v_{mean}$. Each vehicle is set to move along the highway in accordance with the car-following model. Let us consider a couple of consecutive vehicles, referred to as *leader* and *follower*. Over a time interval Δt, a follower vehicle's position $x_f(\cdot)$ is shifted by an amount $\Delta x_f(t)$ given by: $\Delta x_f(t) = \min\{\Delta x_l(t) + h_{lf}(t) - g, v_f(t)\Delta t\}$, where g denotes the minimum spacing between consecutive vehicles that move along the same lane, $\Delta x_l(t)$ is the vehicle's position shift of the leader at time t, and $h_{lf}(t) = |x_l(t) - x_f(t)|$ is the headway between the leader and the follower at time t. We set $g = 25 \ m$ and $\Delta t = 1 \ s$.

As for the communications process, the NS-2 simulator receives as inputs the positions of the vehicles over time, generated according to the mobility model described above. The radio channel path loss follows the two-ray ground model used by NS-2 [30]. The gain $G(d)$ is expressed as in eq. (1). In NS-2, the two exponents are set to $\alpha_1 = 2$ and $\alpha_2 = 4$. The MAC layer module simulates the protocol given by the IEEE 802.11p MAC specification. We invoke the message broadcasting operations mode, under which no ACK frames are produced at the MAC layer. The dissemination logic has been implemented by making use of the ad hoc networking module embedded in NS-2. At the Application Layer, the message flow offered to the RSU is modelled as a constant rate arrival process, so that messages arrive at the application layer of the RSU at fixed time intervals, each of duration of τ_{RSU} seconds. Given a message size of L bits, the RSU offered data bit rate is equal L/τ_{RSU} (bit/s).

In Figure 5, we plot the mean MAC delay $\mathrm{E}[\Theta]$ and the probability of spurious forwarding P_{sf} as a function of the mean vehicular density λ for the three speed values of v_{mean} (90, 110, and 130 km/h), and for the timer parameter $T_{max} = 100 \ ms$. The other parameters are set as stated in Table III. Lines correspond to analytic results while simulation results are reported as dot markers. Solid lines and square dots refer to DBF, dashed lines and triangle markers to TBN. The 95% confidence intervals of the simulations are not visible: they are all less than $6 \cdot 10^{-4} \ ms$ for $\mathrm{E}[\Theta]$ and $1.5 \cdot 10^{-2}$ for P_{sf}.

As for the effect of the variation of the vehicle's mean speed, the graphs depicted in Figure 5 are exemplary of the results obtained for the other considered metrics for both protocols and for other values of λ and T_{max} (not shown for the sake of space). These results are noted to be remarkably unaffected by the change of the v_{mean} level. This is plausible, given the time it takes for a message to propagate along the considered road span. Since, the average hop length is between 700 and 800 m for DBF and is equal to 500 m for TBN, no more than ten hops are required to reach the edge of the road from the RSU, which is placed in the mid point of the road's span.
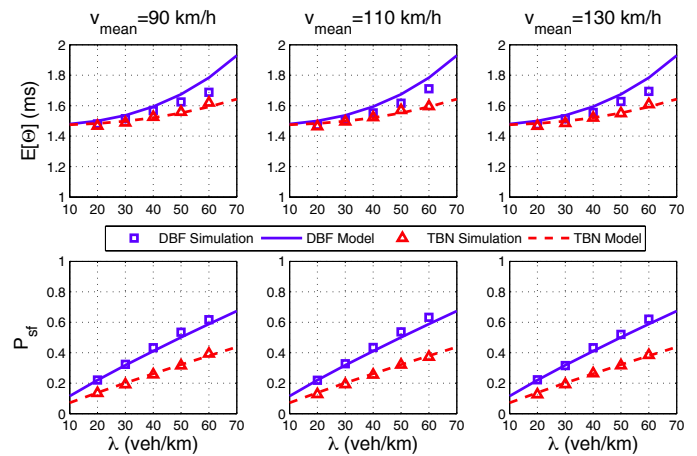

Fig. 5. Comparison between simulation (dot markers) and analytical results (lines) for the mean MAC delay $\mathrm{E}[\Theta]$ and the probability of spurious forwarding P_{sf}. Solid line/square markers: DBF; dashed lines/triangle markers: TBN. Left graphs: $v_{mean} = 90 \ km/h$; central graphs: $v_{mean} = 110 \ km/h$; right graphs: $v_{mean} = 130 \ km/h$. $T_{max} = 100 \ ms$. All other parameter values as noted in Table III.

The highest value noted for a hop delay is around $40 \ ms$, so that the propagation delay of a message from the RSU to the edge does not exceed around $400 \ ms$. This is a rather low time latency, as compared to the vehicular movement time scale. Still, the speed values affect the vehicular interaction process and hence their spatial distribution. The remarkable accuracy of the model points out the adequacy of the Poisson model in accounting for the actual distribution of vehicles along the highway, at least as far as the analysis of message dissemination is concerned in the considered range of v_{mean} levels. In the following, we thus focus on discussing the results obtained for $v_{mean} = 110 \ km/h$.

Figure 6 presents the performance behavior of the mean MAC delay $\mathrm{E}[\Theta]$ and of the probability of spurious forwarding P_{sf} as a function of λ for $T_{max} = 100 \ ms$ (left), $T_{max} = 200 \ ms$ (right), and $v_{mean} = 110 \ km/h$. Figure 7 presents the corresponding performance behavior for the other three metrics; i.e., the mean hop length $\mathrm{E}[Y]$, the mean timer duration of the first (non spurious) forwarder $\mathrm{E}[T]$ and the mean number of spurious forwarders $\mathrm{E}[N]$. The 95% confidence intervals for the results plotted in these graphs never exceed $6 \cdot 10^{-4} \ ms$ for $\mathrm{E}[\Theta]$, $1.5 \cdot 10^{-2}$ for P_{sf}, $1.6 \ m$ for $\mathrm{E}[Y]$, $0.53 \ ms$ for $\mathrm{E}[T]$, and 0.03 for $\mathrm{E}[N]$.

The analytical models produce results that are generally quite close to those obtained by simulations. They consequently support the validity of the simplifying hypotheses used for the analytical model. The random choice of the vehicular speed and vehicular interactions, especially at high density, is carefully taken into account in the simulations of the multi-lane highway. Yet, the simple Poisson spatial distribution model is capable of yielding a good approximation for the calculation of the metrics characterizing the performance of the system in disseminating the RSU's flows along the highway. Overall, we thus conclude that the results shown in the Figures 5, 6 and 7 well confirm the ability of the analytical models to capture the performance behavior of the system for
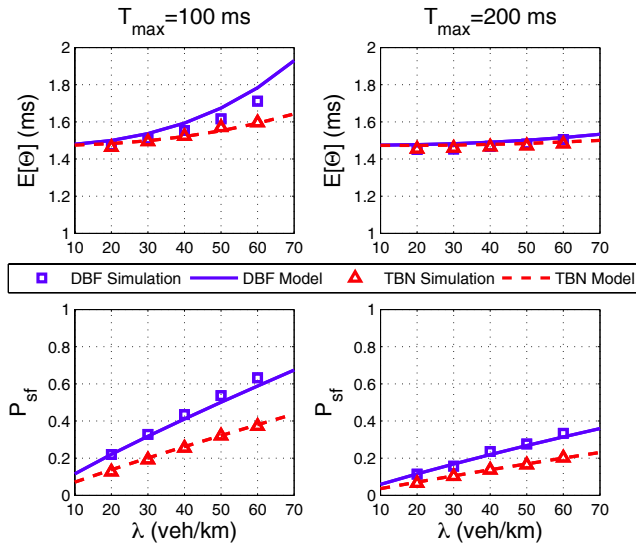
Fig. 6. Comparison between simulation (dot markers) and analytical results (lines) for the mean MAC delay E[Θ] and the probability of spurious forwarding P_{sf}. Solid line curves/square markers: DBF; dashed line curves/triangle markers: TBN. Left graphs: $T_{max} = 100\ ms$; right graphs: $T_{max} = 200\ ms$. $v_{mean} = 110\ km/h$. All other parameter values are set as noted in Table III.
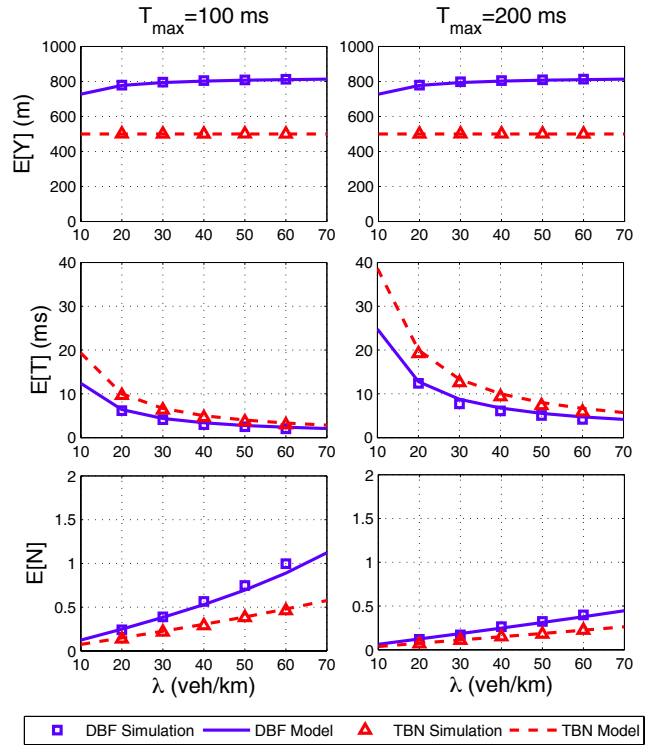

Fig. 7. Comparison between simulation (dot markers) and analytical results (lines) for the mean hop length E[Y], the mean timer duration E[T] and the mean number of spurious forwarding nodes E[N]. Solid line curves/square markers: DBF; dashed line curves/triangle markers: TBN. Left graphs: $T_{max} = 100\ ms$; right graphs: $T_{max} = 200\ ms$. $v_{mean} = 110\ km/h$. All other parameter values are set as noted in Table III.

different values of the average vehicular speed v_{mean} and of the protocol parameter T_{max}.

We observe that the values of P_{sf} and E[N] increase monotonically with the vehicular density λ. This is consistent with what we expect from the two protocols: higher density implies closer vehicles and so a higher probability that a forwarder has a neighbor that is located so close to it that the inhibition rule is not effective. Moreover, the performance figures show that on the one hand this effect triggers an increase in the MAC delay component Θ, while on the other hand, a decrease in the forwarding delay timer T level is induced, since it is increasingly more probable to find a vehicle close to the edge of the hop range (DBF) or to the desired nominal position (TBN). We find that the DBF scheme gives rise to more intense spurious forwarding rates than those caused by using the TBN protocol.

The mean timer delay is noted to be rapidly decreasing with λ. For moderate to high vehicular density levels, the delay is typically lower than $5\ ms$ under both protocols for $T_{max} = 100\ ms$, and it is lower than $10\ ms$ for $T_{max} = 200\ ms$, with DBF achieving lower timer delay values than those attained under TBN. At low vehicular density levels, the message dissemination process becomes more unreliable, since communications disconnects then become more prevalent, especially for very low values of λ (lower than $10\ veh/km$). Even when the propagation process over a relatively long road span ($10\ km$ in our case) is successful, the mean delay per hop is equal to $12\ ms$ (DBF) or $20\ ms$ (TBN) for $\lambda = 10\ veh/km$ and $T_{max} = 100\ ms$ and twice those values for $T_{max} = 200\ ms$. On the other side, it is apparent that both P_{sf} and E[N] are much lower for the higher value of T_{max}, while both increase with λ. To illustrate, consider a moderate vehicular density, namely $\lambda = 40\ veh/km$. The

probability of spurious forwarding is then noted to be close to 0.5 for DBF in case of $T_{max} = 100\ ms$ and it is slightly higher than 0.2 for $T_{max} = 200\ ms$. We observe that there is a trade-off between the value attained for the delay per hop and the increase in occurrence of spurious forwarding events.

The delay per hop, H, can be calculated as the sum of the timer and MAC delay components, $H = T + \Theta$. In case of DBF with $T_{max} = 100\ ms$, the average value of H ranges between $7.92\ ms$ for $\lambda = 20\ veh/km$ down to $4.3\ ms$ for $\lambda = 60\ veh/km$. The average progression speed of a message along the highway is expressed as E[Y]/E[H]. For DBF and $T_{max} = 100\ ms$, it ranges between about $98\ km/s$ up to about $188\ km/s$ for λ that takes values between 20 and $60\ veh/km$.

Finally, all performance metrics except E[Y] are noted to assume similar values, when comparing the DBF and TBN protocols, as the value of T_{max} is increased.

V. DIMENSIONING THE TIMER VALUE RANGE

Given that the spurious forwarding phenomena induced by the non-null MAC delay levels cannot be avoided, we can manage its occurrence as follows. We can set the timer parameters so that the "echo" like tail caused by spurious forwarders fades away before the start of the next hop transmission event. That way, forwarding operations at adjacent RNs do not overlap. The decoupling of events involving forwarding transmissions at relay nodes serves to reduce and limit the

negative effects induced by spurious forwarding events. The pacing of messages offered to the RSU transmission process serves to achieve such RN decoupling effects. In the following, we use the analytical models introduced in Section III to obtain a lower bound on the message sending interval τ_{RSU}. To this end, let $H = \Theta + T$ be the time required for a message to traverse a single RN (single hop traversal time). We derive a (statistical) bound of the time required by a message to traverse the relay chain. This bound is then used to induce the RSU source to impose an admission-control limit on the message sending rate. Using such an admission based flow control operation, the source employs a message pacing operation to limit the rate of messages fed into the vehicular network.

Consider a chain of r RNs[7]. The k-th RN is denoted as RN_k; by extension, we denote the RSU as RN_0. The MAC delay incurred at RN_k, Θ_k, is equal to at least τ_{MAC}. This latency is realized when there is no overlap between the MAC operations of RN_k and of RN_{k-1}, incorporating the spurious forwarders triggered by RN_{k-1}. This decoupled operation can be obtained by setting the timer at each RN at a value that is sufficiently long to allow the transmissions executed at a previous hop to be completed (with high probability) prior to the trigger time of next hop transmissions. Accordingly, we aim at dimensioning the timer value range so that we attain:

$$\mathcal{P}(\Theta_0 = \tau_{MAC}, \Theta_1 = \tau_{MAC}, \ldots, \Theta_r = \tau_{MAC}) \geq 1 - \varepsilon \quad (5)$$

for some suitably small ε, e.g., $\varepsilon = 10^{-3}$. By invoking a renewal process property, justified by the assumed underlying low message rate regime, we have:

$$\mathcal{P}(\Theta_0 = \tau_{MAC}, \Theta_1 = \tau_{MAC}, \ldots, \Theta_r = \tau_{MAC}) =$$
$$= \mathcal{P}(\Theta_0 = \tau_{MAC}) \prod_{j=1}^{r} \mathcal{P}(\Theta_j = \tau_{MAC} | \Theta_{j-1} = \tau_{MAC})$$
$$= [\mathcal{P}(\Theta_B = \tau_{MAC} | \Theta_A = \tau_{MAC})]^r \quad (6)$$

where we denote two generic consecutive RNs as A and B. Hence, the requirement imposed by eq. (5) translates into $\mathcal{P}(\Theta_B = \tau_{MAC} | \Theta_A = \tau_{MAC}) \geq (1 - \varepsilon)^{1/r}$. Note that $\mathcal{P}(\Theta_0 = \tau_{MAC}) = 1$, since the RSU is the source of the messages and it no additional message wait time is incurred at its MAC layer due to its employed message pacing regulation.

Once node A has completed its transmission, and node B has received the new message, B schedules the forwarding of the message by starting its timer T_B; meanwhile N_A spurious forwarders associated with A intend to transmit their (redundant) copies of the message (see Figure 4). The latter take the time $\tau_{MAC} N_A + \nu(N_A)\sigma$ to complete their transmissions, with $\nu(N_A)$ denoting the number of back-off mini-slots counted down to the completion of all N_A frame transmissions.

A lower bound for $\mathcal{P}(\Theta_B = \tau_{MAC} | \Theta_A = \tau_{MAC})$ is obtained as follows. The event $\Theta_B = \tau_{MAC}$ is equivalent to $\tau_{MAC} N_A + \nu(N_A)\sigma \leq T_B$. In turn, that event is implied by $\tau_{MAC} N_A + W_0\sigma \leq T_B$, since $\nu(N_A) \leq W_0$. Under the

[7]The number r of hops is related to the length of the road span from the RSU, ℓ, by the equation $r = \lceil \ell / \mathrm{E}[Y] \rceil$, $\lceil x \rceil$ being the smallest integer no less than x.

condition $\Theta_A = \tau_{MAC}$, N_A is distributed as the Poisson random variable $\tilde{N}$ with mean $\mathrm{E}[\tilde{N}] = b\tau_{MAC}/(T_{max} - T'_{min})$ in case of DBF and $\mathrm{E}[\tilde{N}] = a\tau_{MAC}/(T_{max} - T_{min})$ in case of TBN. We consequently obtain the following lower bound:

$$\mathcal{P}(\Theta_B = \tau_{MAC} | \Theta_A = \tau_{MAC}) =$$
$$= \mathcal{P}(N_A \tau_{MAC} + \nu(N_A)\sigma \leq T_B | \Theta_A = \tau_{MAC})$$
$$\geq \mathcal{P}(N_A \tau_{MAC} + W_0\sigma \leq T_B | \Theta_A = \tau_{MAC})$$
$$= \mathcal{P}(\tilde{N}\tau_{MAC} + W_0\sigma \leq T_B) \quad (7)$$

Setting $\mathcal{P}(\tilde{N} \leq (T_B - W_0\sigma)/\tau_{MAC}) \geq (1-\varepsilon)^{1/r}$ leads to a sufficient condition for meeting the requirement of eq. (5). In this manner, we guarantee that the MAC delay is limited to its minimum value τ_{MAC} for r hops, with a probability that is equal to at least $1 - \varepsilon$. From a networking point of view, this condition implies that, when each RN finally passes its message to the MAC layer, its MAC entity senses the medium to be idle. Hence, the RN MAC delay reduces to $\Theta = \tau_{MAC}$.

Based on the above argument, we set the timer parameters T_{min} and T_{max} so that we attain:

$$\mathcal{P}\left(\tilde{N} \leq \frac{T_{min} - W_0\sigma + (T_{max} - T_{min})\hat{V}}{\tau_{MAC}} \right) =$$
$$= \int_0^1 \sum_{n=0}^{n(v)} \frac{(\mathrm{E}[\tilde{N}])^n}{n!} e^{-\mathrm{E}[\tilde{N}]} f_{\hat{V}}(v) \, dv \geq (1-\varepsilon)^{1/r} \quad (8)$$

where $n(v) = \max\{0, \lfloor (T_{min} + (T_{max} - T_{min})v - W_0\sigma)/\tau_{MAC} \rfloor \}$, and where $\lfloor x \rfloor$ denotes the largest integer not larger than x, $\mathrm{E}[\tilde{N}] = b\tau_{MAC}/(T_{max} - T'_{min})$, $f_{\hat{V}}(v) = be^{-bv}/(1 - e^{-b})$. A similar formula holds when a TBN protocol is used, by just replacing $b = \lambda R$ with $a = \lambda D$ and T'_{min} with T_{min}.

As discussed above, we note that smooth forwarding operations for a continuous flow of messages can be provided if messages are separated in time, so that each message propagates through the forwarding vehicles distributed along the road without interfering excessively with previous and subsequent message transmissions. Interference signals produced by transmissions executed by RNs that are distributed along the highway can be regulated to not impair the reception processes, provided that at most any third RN can transmit at any given time. In other words, we must guarantee (statistically) that the RNs adopt a spatial reuse pattern that is no more dense than a reuse-3 pattern, so that no more than one out of three consecutive RNs are active at the same time. This can be accomplished by pacing the messages emitted at the RSU by spacing them at a time period τ_{RSU} that is no shorter than the statistical bound of the time taken by a message to traverse *two* hops, which is given as $J = H_A + H_B = \Theta_A + T_A + \Theta_B + T_B$.

We statistically upper bound J by means of its quantiles. Applying the targeted timer dimensioning process, we have $\Theta = \tau_{MAC}$ with high probability, and then $J \simeq T_A + T_B + 2\tau_{MAC}$. Hence,

$$\mathcal{P}(J \leq u) \simeq \mathcal{P}(T_A + T_B \leq u - 2\tau_{MAC}) =$$
$$= \mathcal{P}\left(\hat{V}_A + \hat{V}_B \leq \frac{u - 2\tau_{MAC} - 2T_{min}}{T_{max} - T_{min}} \right) \quad (9)$$

TABLE IV
OPTIMAL VALUES OF T_{min} AND T_{max} OBTAINED BY MINIMIZING THE 99TH QUANTILE OF THE TWO-HOP DELAY J, UNDER THE CONSTRAINT OF EQ. (5), IN CASE OF DBF ($R_{max} = R_{th} = 827\ m$).

λ [veh/km]	20	30	40	50	60
T^*_{min} [ms]	6.307	6.307	6.307	6.322	6.307
T^*_{max} [ms]	36.722	51.929	67.137	82.173	97.552
J^*_{99} [ms]	27.806	27.836	27.836	27.851	27.836
TH^* [kbps]	287.712	287.398	287.398	287.241	287.398

TABLE V
OPTIMAL VALUES OF T_{min} AND T_{max} OBTAINED BY MINIMIZING THE 99TH QUANTILE OF THE TWO-HOP DELAY J, UNDER THE CONSTRAINT OF EQ. (5), IN CASE OF TBN ($D = 500\ m$, $R_{th} = 827\ m$).

λ [veh/km]	20	30	40	50	60
T^*_{min} [ms]	6.307	6.307	6.307	6.322	6.307
T^*_{max} [ms]	24.695	33.890	43.084	52.181	61.473
J^*_{99} [ms]	27.801	27.829	27.819	27.838	27.801
TH^* [kbps]	287.760	287.475	287.570	287.380	287.760

The random variables $\hat{V}_A$ and $\hat{V}_B$ are statistically independent, so that we have:

$$f_{\hat{V}_A + \hat{V}_B}(u) = \frac{b(1 - |1 - u|)}{(1 - e^{-b})^2} e^{-bu}, \qquad 0 \le u \le 2. \quad (10)$$

A safe dimensioning of the flow control operation at the RSU imposes a message pacing process that is regulated by setting $\tau_{RSU} = J_q$ for a suitable high value of q, where J_q denotes the value for which $\mathcal{P}(J \le J_q) = q$. The consequent maximum attainable throughput rate is therefore equal to $TH = L/\tau_{RSU} = L/J_q$, where L is the message size. The timer parameters T_{min} and T_{max} can be chosen so as to minimize J_q; i.e., to maximize the achievable throughput rate TH, with outage probability not higher than $1 - q$. For any prescribed ε and q values, the optimal values of T_{min} and T_{max} can be evaluated numerically by minimizing J_q, as calculated by using eqs. (9) and (10), under the constraint expressed by eq. (8).

In the following, we set $q = 0.99$, and hence evaluate J_{99}; i.e., the value that J does not exceed over 99% of the time. As a matter of example, by setting $\varepsilon = 10^{-3}$, $\ell = 5\ km$, $R_{th} = R_{max} = 827\ m$ (corresponding to an air bit rate of 6 Mbps) and a message size $L = 1000\ bytes$, we obtain in case of DBF the performance results displayed in Table IV. Optimal values are denoted with a superscript asterisk.

The results listed in Table IV show that the optimal value of T_{min} is insensitive to the vehicular density λ, whereas the optimal range of the timer $T_{max} - T_{min}$ scales proportionally with λ. By means of this choice of the timer parameters, it turns out that the achievable throughput is insensitive to λ. In contrast, if a constant parameter setting were adopted, the number of spurious forwarders would increase with λ, thus reducing the throughput. The quite conservative design that has led to the values shown in the latter Table yields a stable throughput of about 36 msg/s, for transport along a road that spans a distance of up to 5 km away from the RSU.

Similar considerations apply when considering the TBN protocol, by just substituting b with a, and thus the maximum hop range R_{max} is replaced with the nominal inter-RN distance D. The numerical results are displayed in Table V. It is noted that the optimal values assumed by T^*_{min}, J^*_{99} and TH^* are about equal to the corresponding ones calculated for the DBF scheme. The only exception applies to the value used for T^*_{max}, since it depends directly on the length of the hop that separates two consecutive RNs.

VI. DIMENSIONING THE MAXIMUM HOP RANGE

In this Section, we relax the deterministic reception model and assume that the probability that a message is successfully received at distance x from the transmitting node is $P(x)$. Reception is considered to be successful if the SNR at the receiver exceeds a threshold γ_{th} that depends on the link rate. Under a deterministic path loss model, the latter requirement of a minimum SNR level translates into a sharp maximum transmission range R_{th}. Thus, in this case, reception events are successful at distances that are lower than R_{th} and they fail at distances that are longer than R_{th}. We then write: $P(x) = 1, x \in [0, R_{th}]$ and $P(x) = 0, x > R_{th}$. In general, $P(x)$ varies in a more gradual manner so that it is reduced from 1 towards 0 as x increases.

Timer-based dissemination protocols, as presented in Section II, limit the scope of nodes that participate in the forwarding process, including only those nodes that are located within a distance R_{max} of the transmitting node (*maximum hop range*). The rationale used to configure a hop range value that is limited to a value R_{max} is explained as follows.

Let $x = 0$ be the position of the source node S. When S sends out a message, several of the nodes located in $[0, R_{max}]$ may not receive the message correctly (most probably, those that are located farther away from S). Let $\mathcal{G}_X$ and $\mathcal{F}_X$ denote the set of the nodes within distance R_{max} of node X that successfully receive or fail to receive a message sent out by X, respectively. All nodes belonging to $\mathcal{G}_S$ successfully receive a copy of the message sent by S and initiate their forwarding timers. A node in $\mathcal{G}_S$, say A, whose timer expires first, will then be the first to forward the received message. Its transmission will then inhibit the forwarding of only those other contending nodes that belong to $\mathcal{G}_S \bigcap \mathcal{G}_A$, i.e., that receive *two* copies of the same message[8]. Nodes in the set $\mathcal{F}_S \bigcap \mathcal{G}_A$ do not receive the message from S, yet they receive it (for the first time) from A. Therefore, they schedule the new message for possible forwarding. Similarly, nodes in $\mathcal{G}_S \bigcap \mathcal{F}_A$ receive the message from S, schedule its forwarding, but they do not receive the message forwarded by A, so that no inhibition is triggered. In both cases, the duplicate message suppression process is not effective. Unsuppressed duplicates become more probable as a higher value is configured for R_{max}.

A quantitative assessment of the effect of the value set for R_{max} is carried out by assuming a specific form for $P(x)$. To that end, we assume a Rician fading path loss model (as done, e.g., in [15]), so that the normalized SNR $\hat{\gamma} = \gamma/\overline{\gamma}(x)$ at distance x from the transmitting node is modeled as a random

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[8] Except spurious forwarders. This does not affect the essence of the argument of this Section.

variable whose PDF is expressed as [31]:

$$p_{\hat{\gamma}}(v) = (1 + K)e^{-K}e^{-(1+K)v}I_0(2\sqrt{K(1+K)v})$$

for $v \geq 0$, where $\overline{\gamma}(x)$ is the average SNR value incurred at distance x, K is the ratio between the mean power of the dominating path and the mean power of the other paths, and $I_0(\cdot)$ is the modified Bessel function of the first kind of zero order. We let $G(x)$ denote the deterministic component of the path gain of the radio channel at distance x. Then, $\gamma(x) = G(x)P_{tx}/P_N$, where P_N is the background noise and P_{tx} is the transmission power; $G(x)$ is expressed as described in eq. (1). The setting of the SNR threshold value γ_{th} to induce successful message reception corresponds to setting a distance threshold level R_{th} such that $\gamma_{th} = G(R_{th})P_{tx}/P_N$. Then,

$$P(x) = \int_{\gamma_{th}/\overline{\gamma}(x)}^{\infty} p_{\hat{\gamma}}(v)\, dv = \int_{G(x)/G(R_{th})}^{\infty} p_{\hat{\gamma}}(v)\, dv$$

for $x > 0$.

Let A be the most distant node that successfully receives the message sent by S and let $Y \equiv d_{AS}$. We note that Y is a random variable. Nodes are assumed to be spatially distributed according to a Poisson process with density λ. Let $N(a, b)$ denote a random variable that represents the number of vehicles travelling in the interval (a, b) that successfully receive the message sent by S. Those nodes form an inhomogeneous Poisson process with mean density $\lambda P(x), x > 0$. The cumulative probability distribution function of Y, conditional on there being at least a single successful reception within a distance that is equal to R_{max} from the source node S, is:

$$
\begin{aligned}
F_Y(y) &= \mathcal{P}(Y \leq y | N(0, R_{max}) > 0) = \\
&= \frac{\mathcal{P}(N(y, R_{max}) = 0\ \&\ N(0, y) > 0)}{\mathcal{P}(N(0, R_{max}) > 0)} = \\
&= \frac{e^{\int_0^y \lambda P(u)\, du} - 1}{e^{\int_0^{R_{max}} \lambda P(u)\, du} - 1}, \qquad 0 \leq y \leq R_{max}
\end{aligned}
$$

The conditional PDF of Y is calculated as the derivative of $F_Y(y)$. We consequently obtain:

$$f_Y(y) = \frac{\lambda P(y)e^{\int_0^y \lambda P(u)\, du}}{e^{\int_0^{R_{max}} \lambda P(u)\, du} - 1}, \qquad 0 \leq y \leq R_{max}$$

Let $\mathcal{N}_1(y) = (\mathcal{G}_S \bigcap \mathcal{F}_A) \bigcup (\mathcal{F}_S \bigcap \mathcal{G}_A)$ denote the set of nodes belonging to $(0, R_{max})$ that receive the message exactly once, after both S's and A's transmissions, conditional on the distance between S and A being $Y = y$. Those nodes are distributed in accordance with an inhomogeneous Poisson process with mean density $\lambda_1(x|y) = \lambda[P(x)(1 - P(y - x)) + (1 - P(x))P(y - x)]$ for $x \in [0, y]$ and $y \in [0, R_{max}]$. The conditional average number $M(y) \equiv E[\mathcal{N}_1(y)|Y = y] = \int_0^y \lambda_1(x|y)\, dx$ of such nodes is

$$M(y) = 2\int_0^y \lambda P(x)\, dx - 2\int_0^y \lambda P(x)P(y - x)\, dx$$

The probability that no such node exists is calculated as

$$q_0 \equiv \int_0^{R_{max}} e^{-M(y)} f_Y(y)\, dy$$

The probability that at least one node escapes the inhibition mechanism, i.e., the probability that inhibition is not fully
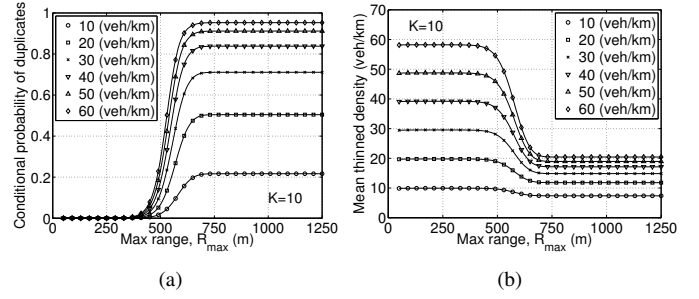

Fig. 8. Duplicate messages under random reception model (Rician channel with $K = 10$): (a) probability that at least one duplicate forwarding arises; (b) mean number of nodes receiving the message in a single hop.

effective and spurious message forwarding actions take place, is $P_{dup} = 1 - q_0$.

The probability of duplicates P_{dup} is plotted in Figure 8 for the case $K = 10$ and $\gamma_{th} = 8\ dB$. The threshold distance R_{th} is obtained by assuming a $10\ MHz$ channel bandwidth, white noise (power spectral density of $-174\ dBm/Hz$), transmission power of $500\ mW$, air bit rate of $6\ Mbps$ in the IEEE 802.11p radio interface, so that $R_{th} = 827\ m$, as displayed in Table I. The high value of the parameter K of the Rician channel model implies that the dominant path accounts for the bulk of the received energy. This is consistent with a highway scenario where propagation occurs in open space and fading due to multiple paths has a marginal effect.

It is apparent that for values of R_{max} of up to about $600\ m$ the probability that a vehicle inside the interval $(0, R_{max})$ receives only a single copy of the message, following the execution of transmissions by both S and A, is negligible. In fact, vehicles in $(0, R_{max})$ almost surely receive two copies of the message, one sent by S and the other one sent by the winning relay node A. The second received copy triggers the inhibition of the scheduled forwarding. For higher values of R_{max}, the probability that duplicates arise because of the ineffectiveness of the inhibition mechanism increases rapidly. To maintain the effectiveness of the inhibition rule, it is effective to limit R_{max} so as to induce a negligible P_{dup} value.

The right plot in Figure 8 depicts the average density of vehicles that successfully receive the message sent by S in the interval $(0, R_{max})$, namely $\lambda_{succ} = \int_0^{R_{max}} \lambda P(x)\, dx$. It stems from the average density λ of the original Poisson vehicle spatial distribution, thinned according to the probability of correct reception $P(x), x \in (0, R_{max})$. We note that that $\lambda_{succ} \approx \lambda$ for values of R_{max} such that P_{dup} is negligible. Since those values are preferred for the dimensioning of the parameter R_{max}, thinning of the vehicular density due to the occurrence of failed message reception events can be neglected. In other words, it turns out that proper dimensioning of R_{max} to avoid spurious forwarding implies that $P(x) \simeq 1$ for $x < R_{max}$.

Similar results have been obtained for lower values of the parameter K of the Rician PDF, as observed even in the extreme case of the Rayleigh channel model ($K = 0$) in Figure 9. For values of R_{max} below $200 - 300\ m$, the probability of duplicated forwarding is very small and thinning
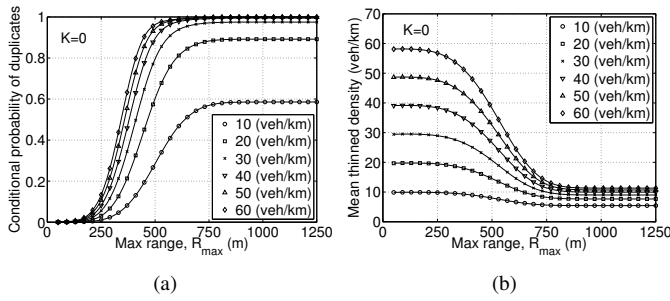
(a) (b)

Fig. 9. Duplicate message under random reception model (Rayleigh channel): (a) probability that at least one duplicate forwarding arises; (b) mean number of nodes receiving the message in a single hop.

(a) 1 msg/s (8 kbps) (b) 10 msg/s (80 kbps)

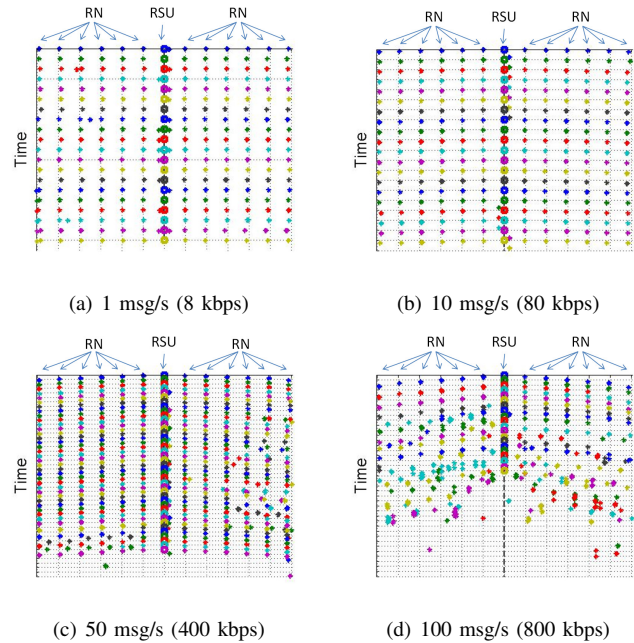(c) 50 msg/s (400 kbps) (d) 100 msg/s (800 kbps)

Fig. 10. Time-space example of DBF dissemination of a message flow from an RSU towards both directions of a road span. Messages correspond to markers, the horizontal axis represents the road line, the vertical axis represents time, growing downwards.

of the vehicular density can be neglected. Higher values of R_{max} are not advisable, since inhibition becomes significantly ineffective, thus reducing the efficiency of the dissemination protocol.

The conclusion drawn from this analysis is that the maximum hop range R_{max} should be limited to achieve good performance of the timer-based dissemination protocol. Once a suitable upper bound is selected for R_{max}, so that this range provides for a reliable message reception process, the random nature of the radio channel impacts the dissemination process in a minor fashion.

VII. DISCUSSION

In assessing the impact of spurious forwarding phenomena, induced by the non null latency involved with the operation of the MAC entity, we note the following. To eliminate the occurrence of spurious forwarding events, one may consider the possible modification of the approach used to carry out the dissemination process. For example, replacing the underlying message-by-message distributed operations with the setting up of a (distributed) RN election procedure. Vehicles that are activated to assume the role of relay nodes (RNs) by an employed election procedure would execute the involved message forwarding tasks, without relying on timer expiration. Such a more elaborate approach is particularly useful if we aim to realize a highly efficient VANET systems that support high data throughput rates. RN election would then adaptively configure the network to achieve best feasible $SINR$ levels, leading to an operation that is carried out at high data rates (e.g., see [32] [33]). In turn, if the realization of high throughput data rates is not the paramount objective (as is often the case when supporting metering/monitoring or safety related critical data dissemination applications), message-by-message forwarding mechanisms can be attractive due to their relative implementation simplicity (noting that essentially no separate signaling sub-system is required). In avoiding requiring re-design of the MAC protocol, it is highly advantageous to implement the dissemination logic on top of the MAC layer. However, as discussed in this paper, such a cross-layer implementation induces the increased occurrence of the spurious forwarding phenomenon. We have shown in this paper that the induced performance degradation can be

limited by using pacing based flow control at the message source and by properly setting the timer parameters.

With the aim of designing a lightweight dissemination protocol, employing no associated signalling or beacon messages, autonomous, timer-based schemes are highly attractive mechanisms. Yet, even when setting a suitable low R_{max} parameter value, these schemes give rise to spurious forwarding phenomena. The models and analyses presented in this paper serve as effective tools for synthesizing the operation, including the dimensioning of the protocol's parameters. The mathematical models presented in this paper provide quantitative assessment of the system's performance behavior under the environment of a *low traffic regime*.

Such autonomous, timer-based dissemination protocols maintain a stable low message delay operation for low message loading rates. As the offered message rate increases above a critical level, the throughput and delay performance of the networking operation will lead to throughput collapse. How much can we increase the message rate without incurring such throughput degradation? To demonstrate the conditions leading to the occurrence of such a collapse event, a time-space diagram, which tracks the message dissemination process of the DBF protocol, is shown in Figure 10. The RSU is located at the center of a road, while the road spans the horizontal axis. Messages issued by the RSU are denoted with square markers, while those forwarded by RNs, which have been self-elected in accordance with the DBF logic, are marked with circles. The involved parameters and models are the same as those used for the simulations presented in Section IV.

The plots exhibited in Figures 10(a)-10(d) refer to controlled message rates $1/\tau_{RSU}$ that are set equal to 1, 10, 50,

$100\ msg/s$, respectively. In Figure 10(a)-10(b) the regular scheme of the time-space diagram highlights the regulation effectiveness through the setting feasibility of the chosen rates: the interaction among successive hops is negligible, so that an ordered chain of regularly spaced RNs can be maintained over time and space, though few spurious forwarding events are noticed. In Figure 10(d), the regular space-time grid breaks down after a short initial transient phase (during which many messages are lost). The interaction between successive RNs leads to an increase in the MAC frame delay level, further exacerbating the impact caused by the induced spurious forwarding phenomena. This in turn increases the medium contention level, further increasing the incurred MAC frame delay. This degenerative spiral causes the ad hoc network to collapse, thus stopping effectively the dissemination of message flows. The graph of Figure 10(c) refers to an intermediate situation, where the system is on the brink of collapsing: a regular grid of RNs is barely maintained and occasional break downs can be observed.

Our model offers a pathway to the implementation of a distributed beacon-less forwarding protocol that enables the system to operate in a stable manner, sustaining throughput rates that induce the system to operate close to the boundary of the break-down zone.

VIII. CONCLUSIONS

timer-based dissemination mechanisms are effective procedures for the implementation of a fully distributed, beacon-less, message forwarding process for a vehicular network system. The underlying forwarding protocol is conveniently executed by each node's network layer entity, residing on top of the radio link layer protocol. We show that the cross-layer interactions induced by such schemes give rise to the occurrence of *spurious forwarding* phenomena.

We present an analytical model that is used to characterize the behavior of spurious forwarding processes, in considering message broadcasting along a linear highway. The precision of our derived analytical models is validated and confirmed through extensive Monte Carlo simulations. The results confirm the high accuracy offered by the analytical model, in spite of its simplicity. The model is also employed to determine the proper dimensioning of the message flow admission control and pacing regulation processes, serving to limit the loading of the network to an optimized message rate level.

Extensions of our approach are of interest in addressing the analysis and design of beacon-less forwarding mechanisms under complex urban transportation scenarios.

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