An OFDMA-Based MAC Protocol for Next-Generation VANETs

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***Abstract*—Vehicular ad hoc networks (VANETs) enable higher safety, enhanced mobility management, and new infotainment services. Currently, the foreseen standard at the medium access control (MAC) layer for VANETs is IEEE 802.11p, which is based on carrier sense multiple access with collision avoidance (CSMA/CA). However, under heavy traffic conditions, CSMA/CA suffers from a high collision probability, particularly in the presence of hidden terminals. Furthermore, the adoption of the request-to-send/clear-to-send (RTS/CTS) mechanism is not effective when a high data rate is required. If high-throughput services are addressed, a new MAC protocol should, thus, be designed. To this aim, in this paper, we propose a new protocol, which is denoted as the orthogonal frequency-division multiple-access (OFDMA)-based MAC protocol for VANETs (OBV), and we compare it with other MAC protocols taken as benchmarks. To verify the feasibility and the performance of the proposed algorithm, we first propose an analytical model in a simplified scenario. Then, we develop exhaustive simulations in realistic scenarios, considering both urban and highway environments. Results show that OBV outperforms all reference protocols, even doubling their throughput under heavy-load network conditions.**

***Index Terms*—Medium access control (MAC) protocols, orthogonal frequency-division multiple access (OFDMA), vehicular ad hoc networks (VANETs).**

I. Introduction

In the next few years, most vehicles will be equipped with wireless communications devices, hereafter denoted as onboard units (OBUs), enabling a variety of new services, such as safety, enhanced traffic management, and new infotainment services [1]–[6]. For this reason, vehicular ad hoc networks (VANETs) are gaining an increasing importance, and great attention is paid on the protocol stack design.

The recognized protocol suite for VANETs is Wireless Access in Vehicular Environment (WAVE), which relies on IEEE 802.11p [7] at the physical (PHY) and medium access control (MAC) layers. Most countries assigned up to seven channels of 10 MHz to short-range vehicular communications, with one channel for control operations and the others for service purposes [8]. At the MAC layer, IEEE 802.11p is based on carrier sense multiple access with collision avoidance (CSMA/CA), which is an obvious solution for distributed networks since it inherently manages a decentralized allocation of resources. However, since the access is based on sensing at the transmitter, CSMA/CA suffers from the hidden terminal problem, which happens any time a receiver is in the range of two transmitters that do not hear each other. The hidden terminal problem leads to a severe performance reduction when the network load increases, as shown, for example, in [9].

For this reason, several alternatives have been proposed in the past years for VANETs, based on code-division multiple access (CDMA), space-division multiple access (SDMA), and time-division multiple access (TDMA) [10]–[18]. All the proposed protocols reduce the impact of the hidden terminal problem, but they are not specifically designed for high-throughput services.

If the main requirement is high efficiency in the use of resources, one interesting alternative is the use of orthogonal frequency-division multiple access (OFDMA). The use of orthogonal frequency-division multiplexing (OFDM) at the physical (PHY) layer allows the system to combine frequency and time multiplexing, providing high spectral efficiency with limited complexity and solving the hidden terminal problem. Due to these characteristics, OFDMA appears to be one of the preferred choices for high-speed communication systems. Indeed, it has been adopted by the most recent cellular-based communication systems, such as Long-Term Evolution and Worldwide Interoperability for Microwave Access [19]–[21]. However, the adoption of OFDMA is currently limited to infrastructured networks, and its use in ad hoc networks has attracted attention only in the past few years [22]–[32].

Motivated by the given considerations, in this paper, we do the following.

1) Propose a new MAC protocol, denoted as OFDMA-based MAC protocol for VANETs (OBV).
2) Derive an analytical model to quantify the throughput of the proposed scheme in a simplified scenario with two hidden terminals and compare it with that of reference protocols.
3) Evaluate the performance of OBV and compare it with that of reference protocols in both a vehicular urban environment with hundreds of vehicles and a highway scenario with 2000 vehicles by means of realistic simulations.

As reference protocols, we consider 1) conventional CSMA/CA; 2) CSMA/CA with request-to-send/clear-to-send (RTS/CTS); and 3) the TDMA-based protocol MS-ALOHA [16].

The remainder of this paper is organized as follows. In Section II, related works are discussed. In Section III, the

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proposed protocol is presented and described in detail, and reference protocols are introduced. Numerical results are provided in Section IV for a simplified scenario, through analysis, and, in Section V for urban and highway scenarios, through simulations. Finally, in Section VI, conclusions are drawn, and open issues are discussed.

II. Related Work

IEEE 802.11p, which is based on CSMA/CA, is currently considered the main candidate for the implementation of VANETs. However, the critical performance degradation that occurs in heavy load conditions, due to the hidden terminal problem, has lead to the proposal of several alternatives in the last years, mainly based on CDMA, SDMA, and TDMA.

The use of CDMA for VANETs is investigated for example in [10]. The critical points for the use of CDMA in VANETs are the choice of the spreading length, the pseudonoise (PN) code allocation, and the power management to avoid the near-far effect. More specifically, longer spreading codes lead to higher protection against interference, whereas shorter spreading codes are required to achieve a higher throughput. Concerning code allocation, since it is unfeasible to have a code per each vehicle, the main problem is how each vehicle should determine the code to be used. Finally, the near-far effect prevents correct transmissions between vehicles due to the large interference caused by nearer nodes. Although CDMA appears as an interesting technique for its delay-free channel access and the inherent protection against interference, the aforementioned problems made CDMA suitable only for some specific cases, such as, for instance, safety applications based on broadcast messages [10].

A second class of protocols is the one based on SDMA, where the choice of the resources to be allocated depends on the position of OBUs. Various SDMA protocols have been proposed depending on the kind of resources to be used: resources are time slots [11], PN codes [12], a combination of time slots and groups of OFDM subcarriers [13], or the various dedicated short-range communication channels [14]. With SDMA, each OBU is allowed to access a subset of all resources, depending on its own position; this could be performed based on GPS coordinates [11]–[13], or following a clustering procedure [14]. Since OBUs that are potentially interfering will be associated to separate resources, collision probability is significantly reduced. However, the main issue with SDMA is that a reuse of resources must be foreseen; the reuse strategy is simple to achieve in the case of a straight road scenario but becomes very complicated to be planned in a realistic urban scenario. It is indeed not surprising that all cited works refer to a highway scenario. In addition to this, there is also the obvious consequence of limited throughput due to the use of a subset of resources.

In the last years, the most investigated alternative to CSMA/CA has been TDMA. Starting from the AD-HOC MAC protocol proposed in [15] for VANETs, several modifications have been successively suggested, including MS-ALOHA [16], VEMAC [17], and CAH-MAC [18]. After an access phase, which is performed with a contention-based procedure, each OBU holds the gained slots in the following frames. To minimize the risk of collision and avoid hidden terminal problems, all OBUs communicate their observed slot occupation to all the neighbors. Obviously, this mechanism introduces an overhead. Typically, it is assumed that one slot is reserved per OBU for transmissions, with the drawback that the number of OBUs simultaneously accessing the medium is upper bounded by the number of slots and that the resources available for each communication are fixed, independently to the real needs. If slots can be allocated on needs, the problem of slot saturation is more likely, and OBUs that do not hold any slot cannot share their slot occupation view.

Although there are several promising protocols for safety-critical communications, where constrains are on reliability and delay, there is a little understanding on protocols suitable for high-throughput communications in VANETs. To overcome this limitation, a possible option, still rarely considered, is the use of OFDMA. In [20] and [21], OFDMA is foreseen for vehicular scenarios, but its application is limited to cellular networks. A few works investigate the use of OFDMA for distributed ad hoc networks. In [22] and [23], for example, OFDMA is exploited to create several parallel communication channels that are then accessed using CSMA/CA. OFDMA is also considered in [24]–[27] by discussing various aspects at PHY, data link, and network layer; however, these works do not consider the issue of resource allocation. In [28] and [29], emphasis is posed on the possibility of concurrent transmissions (or receptions) by a single node, and the allocation process is provided through a separate dedicated channel. To the best of our knowledge, a fair comparison of the performance achievable with CSMA/CA and OFDMA, which should consider the resources that are required for the allocation process, has never been provided for ad hoc networks.

Moreover, if the focus is limited to VANETs, the use of OFDMA has been previously envisioned in few particular cases, such as, for instance, in [30]–[32]. In [30], OFDMA is only used to create separate communication channels to be accessed depending on the position of OBUs and has the same disadvantages of the SDMA protocols. In [31], the focus is on alert message flooding with an OFDMA-based protocol. In [32], a first OFDMA-based protocol is proposed for high-throughput applications in VANETs. With respect to [32], here, we extend the communication protocol, provide an analytical model to assess the performance, and compare our proposal OBV with reference MAC protocols.

III. Orthogonal Frequency-Division Multiple Access-Based Medium Access Control Protocol for Vehicular AD HOC Networks

OBV is thought for high-throughput applications, and its adoption is thus foreseen for service channels.[1] It is also assumed that the settings to be used, including the carrier frequency and the available bandwidth, are specified through the control channel.

To guarantee the orthogonality among subcarriers, all OBUs are required to be time synchronized. This requirement is easily obtainable through the use of GPS receivers, which have

[1]For other applications not requiring high throughput (i.e., safety), other protocols could be used.

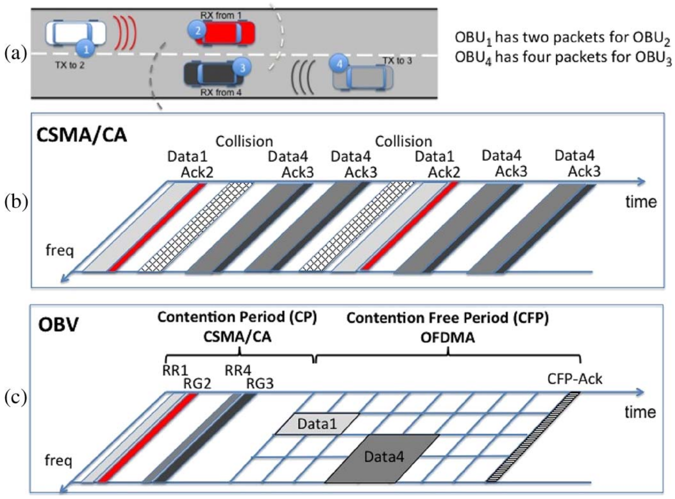

Fig. 1. (a) Example of hidden terminal effect. (b) Time–frequency structure of conventional CSMA/CA. (c) Time–frequency structure of OBV.

typically an accuracy value of less than 100 ns [33], [34]. The temporary absence of the GPS coverage (e.g., in tunnels), can be managed by estimating and correcting the clock drift of the local oscillator, such as in [35]. In the absence of GPS, other techniques for time synchronization should be investigated, such as the timing estimation based on training sequences of neighbors [24] or the time correction commanded by receivers [36]. The design of OBV in the absence of GPS is, however, outside the scope of this paper.

A. Hidden Terminal Problem

To avoid the hidden terminal problem affecting CSMA/CA, the resource assignment of OBV is decided by the receivers instead of the transmitters. To clarify this statement, refer to the scenario shown in Fig. 1(a), where OBU_1 and OBU_4, hidden to each other, address OBU_2 and OBU_3, respectively. By adopting CSMA/CA, OBU_1 and OBU_4 contend for the medium, and the carrier sensing mechanism is not able to reveal a possible ongoing transmission of the competitor; collisions due to the hidden terminal phenomenon are highly probable. When OBV is adopted, the allocation of resources is carried out by OBU_2 and OBU_3 and does not lead to collisions. When, for example, OBU_2 first allocates resource units (RUs) to OBU_1, it also warns OBU_3 that those RUs are busy, and they must not be used by any sender in the range of OBU_2; OBU_3 then allocates orthogonal resources to OBU_4, and OBU_1 and OBU_4 transmit their data without interfering with each other.

B. OBV Protocol

As highlighted by the example, the use of OFDMA requires a resource negotiation phase, but once resources are allocated, transmissions can be performed without contentions on the medium. As results will demonstrate, this leads to a significant performance improvement. Concerning the resource negotiation phase, the service channel of OBV is organized into intervals, here denoted as frames, and each frame is separated into a contention period (CP) and a contention-free period (CFP) (similarly to IEEE 802.15.4 [37]). The CP is accessed through a contention-based algorithm and used to negotiate the resources to be used in the following CFP, whereas the CFP is used for data transmission in the assigned resources.

During the CP, the following are conducted.

1) Resource-request–resource-grant (RR–RG) exchange is carried out using a conventional CSMA/CA approach. The node requiring the allocation of resources transmits an RR and waits the response of the counterpart that grants the allocation through an RG message. Once an RR–RG exchange completes, the requesting OBU and the granting OBU are identified as *OFDMA-transmitter* and *OFDMA-receiver*, respectively.
2) To limit unnecessary transmissions during the CP, no requests will be issued to a device that is identified as an OFDMA-transmitter and no requests will be performed by an OFDMA-receiver.
3) The RR includes the identification of the intended receiver, the amount of data to be transmitted, and a map of the used OFDMA resources (with a single bit per RU denoting which resource is currently free and which is busy) to inform the counterpart about the RUs available at the transmitter side.
4) The RG includes the identification of the granted transmitter and a map of the assigned OFDMA resources to simultaneously communicate the allocation to the transmitter and to inform all devices in the communication range about the RUs they must consider busy (an additional bit per RU is needed for the map in this case to mark the granted RUs).
5) If an OFDMA-transmitter overhears an RG whose map contains some RUs granted to another OBU but corresponding to some of those it was granted to use, then the OFDMA-transmitter excludes those RUs for the transmission in the following CFP. (An example case will clarify this expedient in the following.)

During the CFP, the following are conducted.

6) The CFP starts with a short interframe space (SIFS) period separating data transmission from the CP.
7) Data transmission is performed through OFDMA.
8) Another SIFS period is included before the acknowledgment phase as a guard interval.
9) RUs are acknowledged using OFDMA.

Different from TDMA-based protocols, the allocations performed in the CP are valid only in the following CFP and are reset at the end of the frame.

The procedure executed by the generic OBU is also described in Procedure 1 through pseudocode.

Procedure 1 OBV protocol

```
procedure BY GENERIC OBU
Frame begin:
    OFDMAtx ← false
    OFDMArx ← false
    RUmap ← all RUs are free
    RUreserved ← null
    OBUdest, N_req ← destination and needed RUs
```

```
  if N_req > 0 then
     initialize backoff
CP begin:
  while CP not ended do
     If backoff ends then
        start RR tx with OBUdest, N_req, RUmap
        if RG is received then
           RUreserved ← assigned RUs
           OFDMAtx ← true
        else
           restart backoff
     else if RR rx then
        freeze backoff (if active)
        if not OFDMAtx && OBUdest is my own then
           assign N_a ⩽ N_req free RUs
           start RG tx with updated RUmap
           OFDMArx ← true
           stop backoff (if active)
     else if RG rx (not an answer to my own RR) then
        freeze backoff (if active)
        if OFDMAtx && conflicting allocations then
           free conflicting RUs
        else
           mark allocated resources as busy
CFP begin:
  if OFDMAtx then
     Tx in Ureserved
     Rx corresponding ACKs
  else if OFDMAtx then
     Rx in allocated RUs
     Tx corresponding ACKs
Frame end:
  this frame ends, next begins
  goto frame begin.
```

To better understand the main aspects of OBV, let us consider the example sketched in Fig. 1. In the case of conventional CSMA/CA [see Fig. 1(b)], OBU_1 and OBU_4 contend for the medium, and each transmission is prone to collisions. Due to the hidden terminal problem, some collisions might occur, and the transmission of all packets may require several attempts. In the case of OBV [see Fig. 1(c)], the sending OBUs access the channel only once in the CP, with the RR message requesting the needed RUs; once the RG is received, RUs are allocated and will not be available for the contending OBU. Finally, the transmitters properly allocate data in the CFP adopting OFDMA, and no collision occurs.

To further clarify the procedures in OBV, all possible cases when four vehicles are in the transmission range of only the nearest OBU in each direction, as shown in Fig. 2, are hereafter analyzed.

Case 1: OBU_1 is the first requesting resources; when OBU_2 sends the RG, OBU_3 knows that some RUs are busy and cannot be allocated to OBU_4. In the CFP, OBU_1 and OBU_4 transmit on orthogonal resources.

Case 2: OBU_2 is the first requesting resources; OBU_3 does not overhear the RG sent by OBU_1 and cannot update the map of OFDMA resources to be included in the RR. However, neither OBU_1 nor OBU_4 are interfered by OBU_3 or OBU_2, respectively. Thus, transmissions can be performed in the CFP without collisions, even adopting the same RUs.

Case 3: OBU_1 is the first requesting resources; when OBU_2 sends the RG, OBU_3 knows that some RUs are busy and updates the resource map to be added to its own RR. In the CFP, OBU_1 and OBU_3 transmit on orthogonal resources.

Case 4: OBU_2 is the first requesting resources; the RG sent from OBU_1 cannot be heard by OBU_3 and OBU_4. As a consequence, OBU_3 may allocate the same resources to OBU_4. In this case, however, OBU_2 overhears the RG from OBU_3, and if the same RUs are allocated, it does not transmit during the CFP (following point 5 of the protocol description). In the CFP, either OBU_2 and OBU_4 use orthogonal resources, or only OBU_4 transmits.

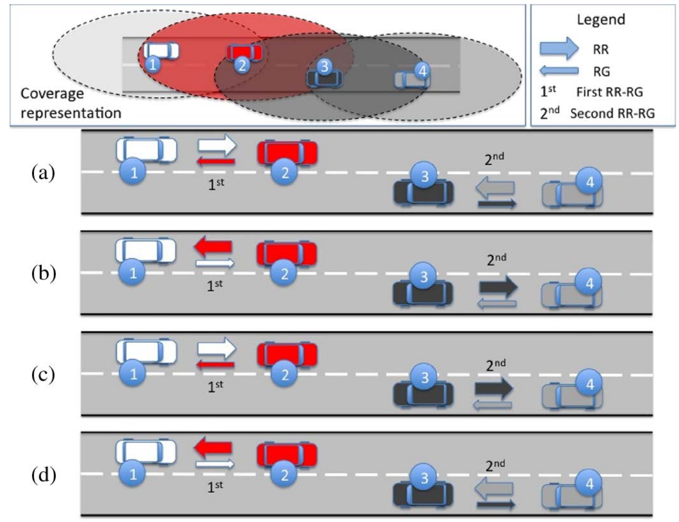

Fig. 2. Reference cases. The topmost part shows the transmission range of OBUs, e.g., OBU_2 is in the range of OBU_1 and OBU_3. The large arrows represent the direction of RR transmissions, whereas the narrow arrows represent the direction of RG transmissions. The number indicates whether the RR–RG exchange is the first or the second to complete.

Note that the four previous cases can be used as a reference to represent all scenarios. It can be shown that any scenario can be studied by considering only two pairs of OFDMA-transmitters (OBU_{T1} and OBU_{T2}) and OFDMA-receivers (OBU_{R1} and OBU_{R2}), where $OBU_{T1} - OBU_{R1}$ is assumed to conclude the RR–RG exchange first. Under such a condition, if OBU_{R2} and OBU_{R1} hear each other, the behavior can be referred to Case (a). If OBU_{R1} and OBU_{R2} do not hear each other, but OBU_{T2} and OBU_{R1} hear each other, the behavior can be referred to Case (c). If OBU_{R1} and OBU_{R2} do not hear each other, OBU_{T2} and OBU_{R1} do not hear each other, and OBU_{T1} and OBU_{R2} hear each other, the behavior can be referred to Case (d). Finally, if OBU_{R1} and OBU_{R2} do not hear each other, OBU_{T2} and OBU_{R1} do not hear each other, and OBU_{T1} and OBU_{R2} do not hear each other, the behavior can be referred to Case (b).

TABLE I
MAIN SYMBOLS AND THEIR VALUES. (∗) DENOTES VALUES THAT ARE USED WHEN NOT OTHERWISE SPECIFIED

PHY and MAC layers from specifications of IEEE 802.11p [7]

Symbol	Meaning	Value
T_{symbol}	OFDM symbol duration	8 μs
T_g	OFDM symbol guard time	1.6 μs
σ	Slot duration	13 μs
T_{SIFS}	SIFS duration	32 μs
T_{DIFS}	DIFS duration	58 μs
n_{W_0}	Minimum contention window	16

OBV Settings

Symbol	Meaning	Value
τ_R	Duration of RR and RG	88 μs (*)
T_F	Duration of the OBV frame	10 ms
T_{CFP}	CFP duration	See Table II
T_{CP}	CP duration	See Table II
N_{RU}	Number of RUs in the CFP	See Table II

Simulation Settings

Symbol	Meaning	Value
d_{tx}	Transmission range in the absence of obstacles and interferers	200 m
δ_{OBU}	Rate of vehicles equipped with OBU	1 (*)
λ	Packet generation rate	1 pack/s (*)
B	Length of packets in byte	100 bytes

Outputs

Symbol	Meaning	Range
S	Average throughput	$\geqslant 0$
ρ_S	Average rate of scheduled requests that receive a grant in a frame	$\in [0, 1]$
D_R	Rate of packets delivered to the RSU	$\in [0, 1]$
L	Average delay from the generation of a packet to the delivery to the RSU	> 0

TABLE II
NUMBER OF RUs AND DURATION OF CP AND CFP. $T_F = 10$ ms

N_{RU}	T_{CP} [ms]	T_{CFP} [ms]
16	4.784	5.216
20	3.504	6.496
24	2.224	7.776
28	0.944	9.056

C. Settings

The main PHY and MAC layer parameters are listed in Tables I and II. To be compatible with IEEE 802.11p, the same parameters are assumed at the PHY layer of OBV for both CP and CFP, with an OFDM symbol duration $T_{\text{symbol}} = 8\ \mu$s and 64 subcarriers (12 of them corresponding to virtual or dc subcarriers). In each symbol, a guard interval $T_g = 1.6\ \mu$s is included; assuming up to $\tau_e = 100$ ns GPS timing synchronization error [33] and a delay spread of $\tau_{\text{ds}} = 250$ ns [38], the guard interval allows a transmission delay $\tau_{\max} = T_g - 2 \cdot \tau_e - 2 \cdot \tau_{\text{ds}} = 900$ ns, corresponding to a maximum distance of 270 m with zero intersymbol interference. Intersymbol interference may occur at larger distances, but the path loss significantly reduces the received power in that case. The most reliable mode of IEEE 802.11p, i.e., binary PSK (BPSK) modulation and convolutional code with rate 1/2 is assumed for data and acknowledgments in all cases.

At the MAC layer, a frame duration $T_F = 10$ ms is assumed, with various possible CP/CFP partitioning, as detailed in Table II. The duration of CP T_{CP} and the duration of CFP T_{CFP} are obtained, starting from the number N_{RU} of RUs assumed per frame. During the CP, the same settings as IEEE 802m11p are assumed also at the MAC layer. RR and RG are supposed of the same duration τ_R; when not differently specified, τ_R is assumed to be of the same duration of an IEEE 802.11p acknowledgment packet, i.e., $\tau_{\text{ACK}} = 88\ \mu$s.

During the CFP, in the frequency domain, the 52 nonnull subcarriers (as in IEEE 802.11p) are grouped into $N_{\text{subch}} = 4$ subchannels. In the time domain, a group of $N_{\text{syts}} = 160$ consecutive OFDM symbols constitutes a time slot. One subchannel and one time slot form an RU, with 2080 subcarriers accommodating $B = 100$ data bytes (convolutionally encoded) plus overhead and pilot symbols. At the end of the CFP, $N_{\text{symAck}} = 4$ OFDM symbols are left for acknowledgments, assuming that three subcarriers plus one pilot subcarrier are used to acknowledge one RU (thus no more than 52 RUs could be acknowledged). Including a SIFS before the data part and a SIFS between data and acknowledgments, the duration T_{CFP} can be evaluated as

$$T_{\text{CFP}} = \lceil N_{\text{RU}}/N_{\text{subch}} \rceil \cdot N_{\text{syts}} \cdot T_{\text{symbol}} + N_{\text{symAck}} \cdot T_{\text{symbol}} + 2 \cdot T_{\text{SIFS}} \quad (1)$$

where T_{SIFS} is the duration of a SIFS. Obviously, the duration T_{CP} of CP can be obtained as

$$T_{\text{CP}} = T_F - T_{\text{CFP}}. \quad (2)$$

D. Reference MAC Protocols

To verify the performance of OBV, the following MAC protocols are considered for comparison.

- *CSMA/CA* protocol foreseen by IEEE 802.11p. Comparing the CP of OBV and CSMA/CA, we can observe that 1) RR and RG with OBV are shorter than CSMA/CA messages and, thus, are affected by a lower collision probability; 2) a single RR–RG exchange can be exploited by OBV to transmit several packets in the CFP, with lower overhead; and 3) during the CP, no further attempts are performed by an OBU that have already received an RG, by an OBU that was identified as OFDMA-receiver, and by an OBU whose destination was identified as OFDMA-transmitter.
- *CSMA/CA with RTS/CTS* protocol, where the exchange of RTS and CTS messages, as foreseen by the other IEEE 802.11 versions, is added to reduce the effect of hidden terminals. The drawback compared with CSMA/CA is a higher overhead.
- *MS-ALOHA 1 slot*. This is the MS-ALOHA scheme where each OBU attempts to reserve one and only one slot. This choice maximizes the probability that all OBUs have a reserved slot and that the view of the slot occupation is correctly shared by all OBUs, thus minimizing the probability of collisions due to hidden terminals. The drawback is that the throughput per device is limited to the capacity of one slot per frame.
- *MS-ALOHA minimum 1 slot*. This is the MS-ALOHA scheme where each OBU attempts to reserve at least one slot; however, the number of slots can be increased if

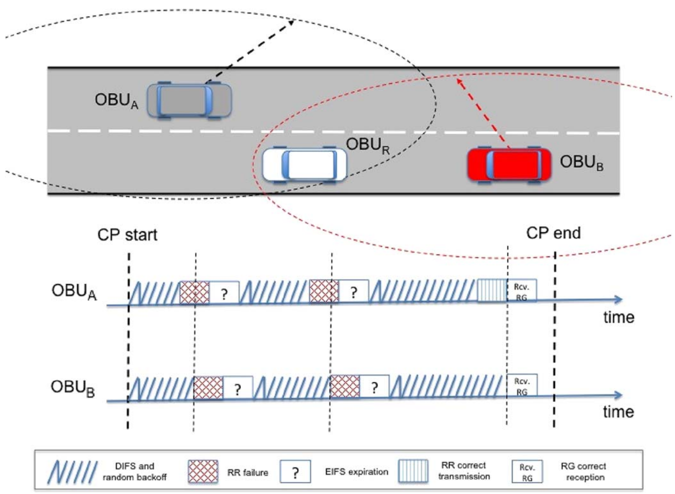

Fig. 3. Simplified scenario with two hidden OBUs and example of evolution of the CP. In the example, $\mathrm{OBU_A}$ correctly transmits the RR at the third attempt.

more packets have to be transmitted. To avoid instability, the number of reserved slots can be increased only by one per frame. The drawback of this approach is that under heavy-load network conditions, OBUs acquiring more slots might make some OBUs unable to acquire a slot (the minimum quantity); those OBUs will thus not be able to share the slot occupation information, and the probability of hidden terminals increases.

- *MS-ALOHA as needed*. This is the MS-ALOHA scheme where OBUs request resources only if they have packets to send. When packets are present, OBUs try to increase the number of reserved slots up to the number of queued packets. Moreover, in this case, the number of reserved slots can be increased only by one per frame. When no slots are reserved, the slot occupation information is not shared.

For the choice of the system parameters, the length of RTS and CTS in the CSMA/CA is assumed equal to τ_{ACK}. As far as MS-ALOHA is concerned, using the IEEE 802.11p PHY layer, frames are supposed of 100 slots, each lasting 1 ms and accommodating the transmission of one 100 B data packet [16], [17]. For fairness of comparison, we assume a 3 Mb/s nominal data rate at the PHY layer; settings are in accordance with the values used in [16] and [17]. Since the mechanism of transmission of acknowledgment messages was not detailed in the references, to deal with the cases where the receiver does not hold any slot, we assume that acknowledgments are transmitted in the control channel. The impact of acknowledgments in the control channel is supposed to be negligible.

IV. Analytical Formulation for the Case Study of Two Hidden Onboard Units

To provide a first performance assessment of OBV, the throughput of the proposed protocol is analytically derived in a simplified three-vehicle scenario. As shown in Fig. 3, the considered scenario consists of two OBUs hidden to each other, which continuously transmit to the same receiver $\mathrm{OBU_R}$ (saturation conditions).

A. Problem Definition

Performance is here investigated in terms of the total throughput perceived by $\mathrm{OBU_R}$, receiving data from $\mathrm{OBU_A}$ and $\mathrm{OBU_B}$ (see Fig. 3). In the proposed protocol, throughput is strictly related to the probability that a node correctly transmits the RR and correctly receives the corresponding RG. In such conditions, once the RR–RG exchange is completed, OFDMA RUs are reserved, and no collision may occur. The problem can be formulated as follows.

- Two OBUs $\mathrm{OBU_A}$ and $\mathrm{OBU_B}$, which are hidden to each other, have packets to be transmitted to the same receiver, i.e., $\mathrm{OBU_R}$ (saturation conditions).
- OBUs demand for all RUs of the following CFP; therefore, all RUs are allocated once the RR–RG exchange has been completed in the CP.
- Since no collision occurs during the transmission of the RG, the RR–RG exchange completes if and only if the RR is correctly received by $\mathrm{OBU_R}$.
- If one RR is correctly received by $\mathrm{OBU_R}$, then all RUs are allocated, and no other RR–RG exchange can be completed in the CFP.
- Defining p_S as the RR success probability, which is the probability that either $\mathrm{OBU_A}$ or $\mathrm{OBU_B}$ correctly transmits the RR in the CP, the average throughput at the receiver S (in bits per second) can be calculated as

$$S = p_S \cdot \frac{N_{\mathrm{RU}} \cdot B \cdot 8}{T_F}. \quad (3)$$

Using (3), throughput is obtained once p_S is known. Since p_S corresponds to the probability that either $\mathrm{OBU_A}$ or $\mathrm{OBU_B}$ correctly transmits the RR in the CP, the problem is eventually moved to the CSMA/CA mechanism of the CP phase. CSMA/CA schemes have been extensively studied in the past years [39]–[42]. However, even if there are several models for CSMA/CA with hidden terminals under both saturated and non-saturated conditions, they are based on the assumption of stationary conditions where all nodes are not synchronized, each node attempts to access the channel until a correct transmission is completed, and the process is repeated after a successful transmission. Here, on the contrary, all nodes are synchronous, transmission attempts are stopped as soon as the CP expires, and no other action is performed if an RR–RG exchange is completed.

B. Analytical Model

Assume CP is divided into slots lasting σ, with σ equal to the slot of the contention phase of IEEE 802.11p. The duration of CP and distributed interframe space (DIFS) in slots can be approximated by $n_{\mathrm{CP}} \triangleq \lfloor T_{\mathrm{CP}}/\sigma \rfloor$ and $n_{\mathrm{DIFS}} \triangleq \lceil T_{\mathrm{DIFS}}/\sigma \rceil$, where T_{DIFS} is the duration of DIFS. Furthermore, we assume that the transmission of RR and RG require the same time τ_R, that can be approximated to $n_{\tau_R} \triangleq \lceil \tau_R/\sigma \rceil$ slots.

As described in Section III, we consider the exponential backoff procedure of IEEE 802.11p; with such an approach, each OBU first senses the medium for a DIFS period, then waits for a backoff period, and finally performs the transmission.

With the contending OBUs being hidden to each other, the medium is not sensed busy, except during the RG transmission. The duration of the backoff period, in slots, is equal to n_{b_i}, where n_{b_i} is randomly chosen in the interval $[0, n_{W_i} - 1]$, i is the attempt number, and $n_{W_i} = n_{W_1} \cdot 2^{(i-1)}$, with n_{W_1} being a constant value given by the standard. If a collision occurs, both $\mathrm{OBU_A}$ and $\mathrm{OBU_B}$ wait for the expiration of an extended interframe space (EIFS) before performing a new attempt. The duration of EIFS can be evaluated as

$$T_{\mathrm{EIFS}} = T_{\mathrm{SIFS}} + T_{\mathrm{RG}} \tag{4}$$

and can be approximated to n_{τ_R} slots ($T_{\mathrm{EIFS}} \approx T_{\mathrm{RG}}$). The parameter values, as dictated for IEEE 802.11p by [7], are listed in Table I and an example of this procedure is shown in Fig. 3, where $\mathrm{OBU_A}$ correctly transmits the RR at its third attempt.

Now, to obtain p_S, first assume that exactly one attempt is possible before CP expires, and any value of n_{b_1} is admissible. In this case, the contending OBUs will collide if $|n_{b_1}^A - n_{b_1}^B| < n_{\tau_R}$, where A and B are used to identify $\mathrm{OBU_A}$ and $\mathrm{OBU_B}$, respectively. Defining $p_{\Delta_i}(k)$ as the probability that $\Delta_i \triangleq n_{b_i}^A - n_{b_i}^B$ is equal to k slots (where k can also be negative), it can be written as

$$p_{\Delta_i}(k) = \begin{cases} (n_{W_i} - |k|)/n_{W_i}^2, & |k| < n_{W_i} \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

and we can write $p_F^{(1)}$, which is the failure probability after one attempt, as

$$p_F^{(1)} = \sum_{\delta_1 = -n_{\tau_R}+1}^{n_{\tau_R}-1} p_{\Delta_1}(\delta_1). \tag{6}$$

The corresponding probability of success using one attempt can be written as $p_S^{(1)} = 1 - p_F^{(1)}$.

Similarly, assuming that at most two attempts are possible before CP expires, and that any values of n_{b_1} and n_{b_2} are admissible, we can evaluate the failure probability with two attempts as the probability to fail at both the first and second attempts, i.e.,

$$\begin{aligned} p_F^{(2)} &= \sum_{\delta_1 = -n_{\tau_R}+1}^{n_{\tau_R}-1} \left[p_{\Delta_1}(\delta_1) \cdot \sum_{\delta_2 = \delta_1 - n_{\tau_R}+1}^{\delta_1 + n_{\tau_R}-1} p_{\Delta_2}(\delta_2) \right] \\ &= \sum_{\delta_0 = -n_{\tau_R}+1}^{n_{\tau_R}-1} \sum_{\delta_2 = \delta_1 - n_{\tau_R}+1}^{\delta_1 + n_{\tau_R}-1} p_{\Delta_1}(\delta_1) p_{\Delta_2}(\delta_2). \end{aligned} \tag{7}$$

Increasing the number of possible attempts, it is straightforward to demonstrate that, for any $m > 0$, the failure probability after at most m attempts, with no any limitation on the random backoff choices, can be written as in (8), shown at the bottom of the page, where

$$\delta_{S_N} \triangleq \begin{cases} \sum_{i=1}^{N} \delta_i, & N > 0 \\ 0, & N \leqslant 0. \end{cases} \tag{9}$$

Unfortunately, the maximum number of attempts is a random variable (RV) as it depends on the length of the backoff intervals. Furthermore, at the last attempt, the backoff interval might be too long to send the RR before CP expiration. To take these aspects into account, we will proceed with the following approximation. Assuming μ as the RV representing the maximum number of attempts, we will 1) derive an estimation $\hat{\mu}$ of the maximum number of attempts before CP expires; 2) evaluate an approximation of the probability that the last attempt is stopped due to CP expiration; and 3) obtain an approximated failure probability at the $\hat{\mu}$th attempt.

Specifically, the maximum number of attempts before CP expires is estimated, considering an average backoff interval for all attempts that precede the last one and the maximum backoff interval for the last attempt, as

$$\begin{aligned} \hat{\mu} = \arg\min_{m \in \mathbb{N}} \Bigg\{ m \cdot n_{\mathrm{DIFS}} + \left\lceil \sum_{j=1}^{m-1} (n_{W_j} - 1)/2 \right\rceil \\ + (n_{W_m} - 1) + 2 \cdot m \cdot n_{\tau_R} > n_{\mathrm{CP}} \Bigg\}. \end{aligned} \tag{10}$$

Assuming that $\hat{\mu} - 1$ attempts have been performed with the average backoff interval, at the $\hat{\mu}$th attempt, the number of backoff intervals that are not acceptable due to CP expiration are

$$\begin{aligned} n_{\exp_{\hat{\mu}}} = \hat{\mu} \cdot n_{\mathrm{DIFS}} + \left\lceil \sum_{j=1}^{\hat{\mu}-1} (n_{W_j} - 1)/2 \right\rceil \\ + (n_{W_{\hat{\mu}}} - 1) + 2 \cdot \hat{\mu} \cdot n_{\tau_R} - n_{\mathrm{CP}}. \end{aligned} \tag{11}$$

Starting from (11), the probability that RR–RG cannot be completed due to CP expiration, even if the backoff intervals chosen at the $\hat{\mu}$th attempt by the contending OBUs do not cause a collision, can be calculated as

$$p_{\mathrm{CP}\exp|\hat{\mu}} = \frac{n_{\mathrm{outCP}_{\hat{\mu}}}}{n_{W_{\hat{\mu}}}^2} \tag{12}$$

where

$$n_{\mathrm{outCP}_{\hat{\mu}}} = \begin{cases} 2 \cdot \left(\sum_{n=1}^{n_{\exp_{\hat{\mu}}} - n_{\tau_R}} n \right), & n_{\exp_{\hat{\mu}}} > n_{\tau_R} \\ 0, & \text{otherwise.} \end{cases} \tag{13}$$

The probability that the RR–RG exchange fails at the $\hat{\mu}$th attempt for either collision or CP expiration, given that the

$$p_F^{(m)} = \sum_{\delta_1 = \delta_{S_0} - n_{\tau_R}+1}^{\delta_{S_0} + n_{\tau_R}-1} \sum_{\delta_2 = \delta_{S_1} - n_{\tau_R}+1}^{\delta_{S_1} + n_{\tau_R}-1} \cdots \sum_{\delta_m = \delta_{S_{m-1}} - n_{\tau_R}+1}^{\delta_{S_{m-1}} + n_{\tau_R}-1} p_{\Delta_1}(\delta_1) p_{\Delta_2}(\delta_2) \cdots p_{\Delta_m}(\delta_m) \tag{8}$$

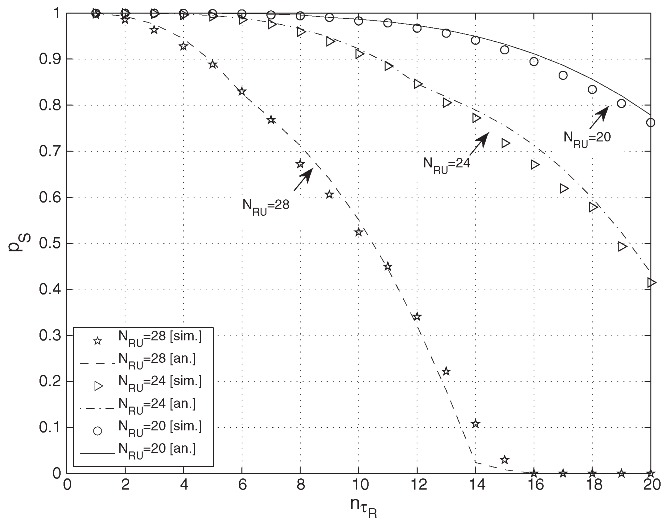

Fig. 4. Two hidden terminals scenario. Success rate of OBV Versus RR and RG duration. Comparison between analysis and simulation.

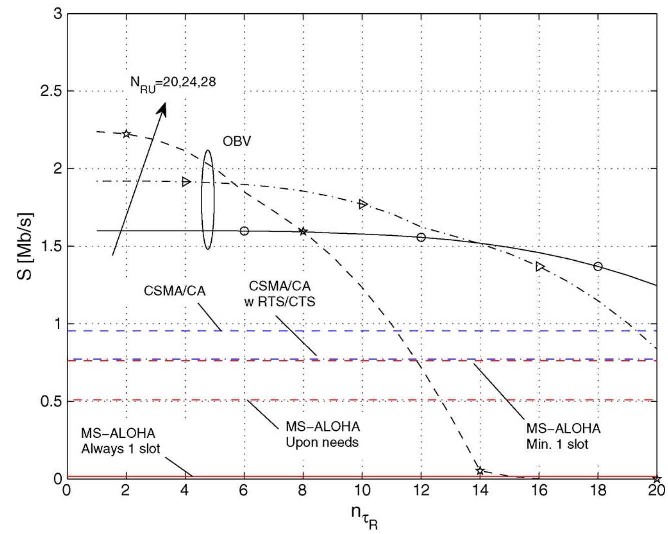

Fig. 5. Two-hidden-terminal scenario. Throughput versus RR and RG duration. Comparison between OBV and reference MAC protocols,

backoff intervals of the last attempt start with k slots of difference, can thus be approximated as

$$p^*_{F_{\hat{\mu}}}(k) \approx \begin{cases} \sum_{\delta_{\hat{\mu}}=k-n_{\tau_R}+1}^{k+n_{\tau_R}-1} p_{\Delta_{\hat{\mu}}}(\delta_{\hat{\mu}}) + p_{\mathrm{CP\,exp}|\hat{\mu}}, & n_{\exp_{\hat{\mu}}} < n_{W_{\hat{\mu}}} \\ 1, & \text{otherwise.} \end{cases} \quad (14)$$

Finally, by calculating $\hat{\mu}$ from (10) and using (14), the probability of success p_S can be approximated as in (15), shown at the bottom of the page.

The validity of (15) is proved in Fig. 4, where p_S is shown varying n_{τ_R}, for various values of N_{RU} (corresponding to different T_{CP} and T_{CFP}, as in Table II). Results show that the approximation (15) is very tight compared with Monte Carlo simulations. Note that no approximation is introduced in the simulations on CP, SIFS, DIFS, and EIFS duration.

C. OBV Versus Reference Protocols

Fig. 5 shows the throughput of OBV, given by (3), and the reference protocols, obtained using simulations, for the two hidden OBUs scenario (see Fig. 3). Results are provided as a function of τ_R and N_{RU} (which imply the use of different values of T_{CP} and T_{CFP}). By comparing OBV with CSMA/CA, the proposed algorithm provides a throughput that is two to three times higher than the reference protocols for reasonable values of τ_R and T_{CP}. Note that the use of RTS/CTS in this scenario does not provide the expected throughput increase; the reduction of collision probability is not enough to balance the overhead introduced by the RTS/CTS exchange. MS-ALOHA provides the lowest throughput. The best choice for MS-ALOHA is the *minimum 1 slot* allocation; a single slot per OBU limits the throughput significantly, and the case with no minimum allocation makes the receiver unable to inform transmitters on the slot assignment.

Focusing on the curves related to OBV, it can be observed that the duration of CP and CFP has to be accurately designed: A large value of N_{RU} may lead to a higher throughput, but the value of τ_R should be sufficiently small. For large values of τ_R, the CP might be too short, causing many RR–RG failures. In the two-hidden-terminal scenarios, it is preferable to use $N_{\mathrm{RU}} = 24$ for $n_{\tau_R} \geqslant 6$, and $N_{\mathrm{RU}} = 20$ for $n_{\tau_R} \geqslant 14$. In summary, OBV outperforms all other MAC protocols, even with a short CP. In general, the best results are obtained with T_{CP} equal to 2.224 or 3.504 (i.e., when $N_{\mathrm{RU}} = 24$ and $N_{\mathrm{RU}} = 20$, respectively).

V. Simulations in Realistic Scenarios

Here, a comparison of *OBV* and reference MAC protocols is provided through simulations, focusing on both an urban scenario with hundreds of vehicles and a highway scenario with 2000 vehicles.

A. Assumptions and Simulation Settings

1) Simulation Tools: Since both vehicular mobility and wireless communication protocols have a relevant impact on the overall performance, their joint effect has been considered by using a simulation tool that integrates both a vehicular traffic simulator, i.e., VISSIM [43], and a wireless network simulator, i.e., SHINE [44], [45]. In particular, VISSIM is a microscopic traffic simulator that reproduces the movements of vehicles on roads, allowing to consider realistic origins and destinations, and movements constrained by the 3-D structure of vehicles and

$$p_S \approx 1 - \sum_{\delta_1=\delta_{S_0}-n_{\tau_R}+1}^{\delta_{S_0}+n_{\tau_R}-1} \sum_{\delta_2=\delta_{S_1}-n_{\tau_R}+1}^{\delta_{S_1}+n_{\tau_R}-1} \cdots \sum_{\delta_{\hat{\mu}-1}=\delta_{S_{\hat{\mu}-2}}-n_{\tau_R}+1}^{\delta_{S_{\hat{\mu}-2}}+n_{\tau_R}-1} p_{\Delta_1}(\delta_1) p_{\Delta_2}(\delta_2) \cdots p_{\Delta_{\hat{\mu}-1}}(\delta_{\hat{\mu}-1}) p^*_{F_{\hat{\mu}}}(\delta_{S_{\hat{\mu}-1}}) \quad (15)$$

Fig. 6. Urban scenario. Road network and RSU position.

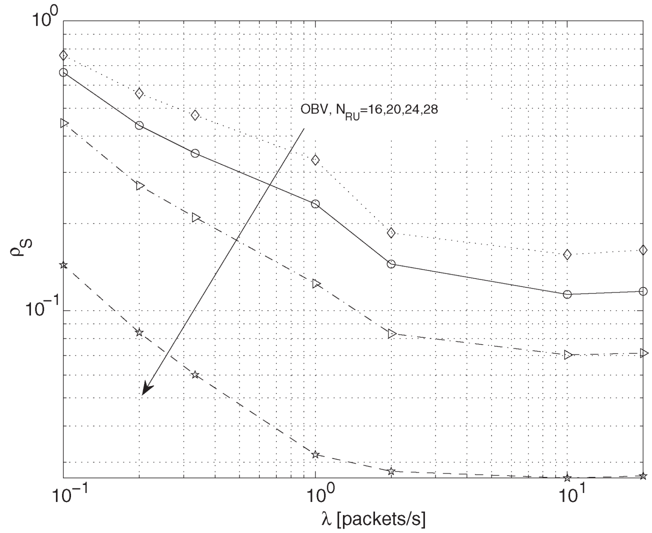

Fig. 7. Urban scenario. RR–RG exchange success rate in OBV versus packet generation rate for various N_{RU}.

by road rules. SHINE is a wireless network simulator designed and developed in our laboratories to carefully take into account the whole protocol stack, from the application to the PHY layer. Concerning the PHY layer, a threshold model is assumed for the packet error rate. The model also includes a hiding effect due to buildings. Specifically, a transmission between two devices occurs only if 1) the virtual line connecting them does not cross any building, 2) the received power is higher than the receiver sensitivity, and 3) the signal-to-noise-plus-interference ratio (SINR) ratio is higher than a threshold. We assume an effective radiated power value of 23 dBm, an antenna gain at the receiver of 3 dB, receiver sensitivity of -85 dBm (as from [7]), a threshold for the SINR of 10 dB, and an attenuation $\mathrm{PL}(d) = 47.9 + 27.5\log_{10}(d)$ [46], where d is the distance in meters. With the assumed parameters, the maximum communication distance in the absence of obstacles and interferers d_{tx} is 200 m.

2) Scenarios: Two scenarios, each including a single roadside unit (RSU), are considered. The first one is an urban scenario corresponding to a portion $(1.6 \times 1.8\ \mathrm{km}^2)$ of the medium-sized Italian city of Bologna, with the road-network layout shown in Fig. 6 [47]. In this scenario, the RSU is deployed in the mostly crowded junction, and 670 vehicles are present on average. The second one corresponds to a straight highway, 13.5 km long, with three lanes per direction. The RSU is deployed in the middle point, and 2031 vehicles are present on average. The digital map of the Italian road network has been provided by Tele Atlas and is used by VISSIM to generate patterns of vehicular mobility. A variable portion of vehicles, i.e., δ_{OBU}, is equipped with the OBU.

3) Channels and Beaconing: OBUs are provided with a dual-radio device able to simultaneously communicate over the control channel and one service channel. CSMA/CA is always assumed for the control channel, whereas either OBV or one of the reference MAC protocols is adopted for the service channel. In the control channel, each OBU periodically transmits beacon messages, including its own position at 10-Hz rate. OBUs know their own position through GPS.

4) Application: As for the application, we assume that all OBUs periodically generate packets of B bytes to be delivered to the RSU. (The RSU, in turn, addresses a remote server through a wired high-speed connection.) Data transmission is carried out using the service channel. If the OBU is under coverage of an RSU, there is a direct data transmission between the OBU and the RSU. Otherwise, a greedy forwarding-based routing scheme is applied. In particular, the OBU, which also knows the position of all its neighbors through the beaconing mechanism, considers as possible relays those that are closer to the destination; the OBU then forwards data to the relay that is closest to the destination. In the case that no other OBU is closer to the destination, the data are stored.

5) Output Metrics: Results are here provided in terms of the following metrics:

- average RR–RG exchange success rate ρ_S, corresponding to

$$\rho_S \triangleq \frac{n_{\mathrm{RG}}}{n_{\mathrm{RR}}} \tag{16}$$

where n_{RR} is the number of requests attempted, and n_{RG} is the number of grants correctly received;

- delivery rate D_R, which is the rate of packets that are delivered to the RSU

$$D_R \triangleq \frac{n_{\mathrm{RSU}}}{n_{\mathrm{gen}}} \tag{17}$$

where n_{RSU} is the number of packets transferred to the RSU, and n_{gen} is the overall number of packets generated;

- average delivery delay L, i.e.,

$$L \triangleq \frac{\sum_{i=1}^{n_{\mathrm{RSU}}} \left(t_{\mathrm{RSU}_i} - t_{\mathrm{gen}_i}\right)}{n_{\mathrm{RSU}}} \tag{18}$$

where t_{RSU_i} is the instant when the ith packet reaches the RSU, and t_{gen_i} is the instant when it was generated.

B. OBV Versus Reference Protocols in the Urban Scenario

In Figs. 7 and 8, we assume that all vehicles in the scenario are equipped with the OBU (i.e., $\delta_{\mathrm{OBU}} = 1$), and results are provided as a function of the packet generation rate λ. The performance of OBV (with four different values of N_{RU}) is compared with that of the reference protocols.

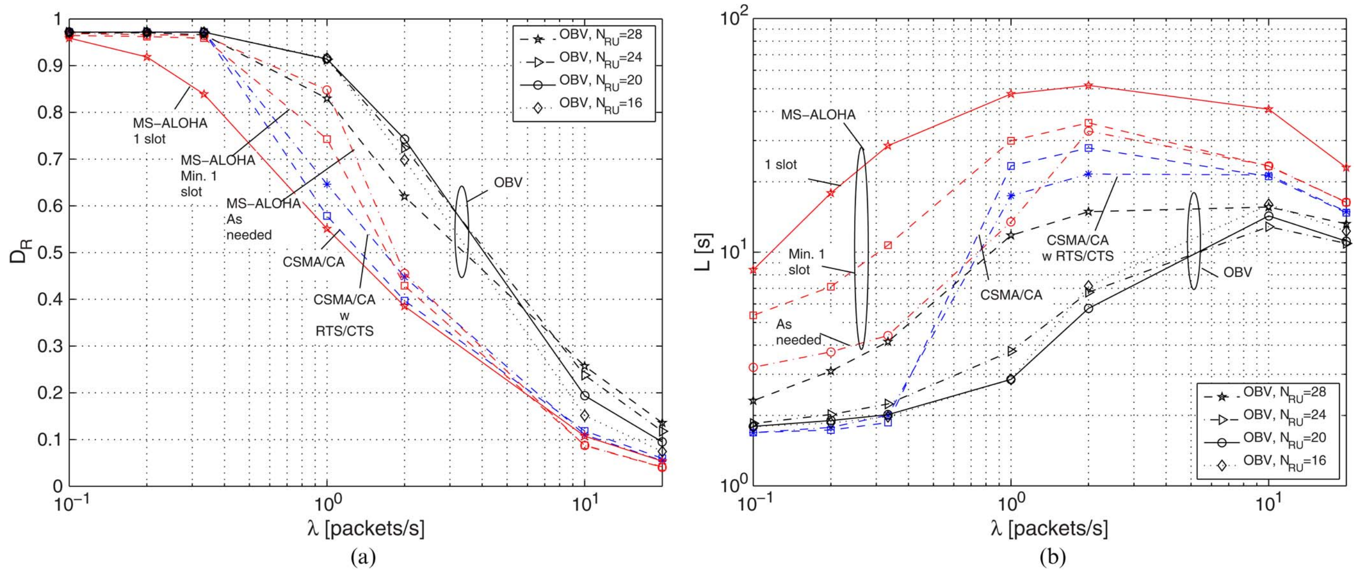

Fig. 8. Urban scenario. Delivery rate and average delay varying the network load. Comparison between OBV, with various N_{RU}, and reference protocols. (a) Delivery rate versus network load. (b) Average delay of packet delivery at the RSU versus network load.

Fig. 7 shows ρ_S as a function of λ. As expected, ρ_S increases with T_{CP} (it decreases as N_{RU} increases) and decreases with λ. Interestingly, ρ_s tends to be constant when $\lambda > 1$. This behavior is due to the fact that OBUs are no longer able to empty their queue, and the number of RR tends to be constant.

Note that, even if ρ_S increases with T_{CP}, a larger T_{CP} does not always lead to a higher D_R. This behavior can be observed in Fig. 8(a), where D_R is plotted as a function of λ. Focusing on the four curves related to OBV, a longer CP (therefore a smaller N_{RU}) appears to be preferable with a limited value of λ (i.e., $\lambda \leqslant 1$); in such a case, a higher value of T_{CP} increases the probability that OBUs complete the RR–RG exchange, thus increasing the rapidity of emptying their queue. This behavior reduces the number of OBUs that simultaneously attempt to transmit the RR and also reduces the collision probability. When λ increases, many OBUs cannot empty their queue before new packets are generated, and they will attempt new RR transmissions in the following frames. In such situation an increase in N_{RU} provides a higher D_R, even if T_{CP} is smaller. It can be also observed that different values of N_{RU}, ranging from 16 to 24, give similar performance, and $N_{\mathrm{RU}} = 20$ appears to be a good compromise for the different traffic conditions.

By observing Fig. 8(a), CSMA/CA, with or without RTS/CTS, is shown to provide worse performance than OBV, with D_R rapidly decreasing when λ exceeds 0.5 packets/s. (The use of RTS/CTS in CSMA/CA gives some benefit for small values of network load.) This behavior can be explained by observing that, when the network load increases, collisions also increase, and more transmission attempts are performed by the OBUs. A different behavior is shown with OBV; in this case, we recall that only a single RR per frame can be transmitted by each OBU, independently on how many packets are queued. For this reason, the difference, in terms of delivery rate, between OBV and the other protocols increases when λ increases.

Fig. 8(a) also shows that OBV outperforms MS-ALOHA. Even if *MS-ALOHA as needed* provides slightly higher D_R than OBV with $N_{\mathrm{RU}} = 28$ when $\lambda = 1$, under heavy-loaded network conditions ($\lambda \geqslant 10$), the same scheme causes the lowest D_R due to the lower probability of having at least one slot available to share the occupation view.

In general, OBV with $N_{\mathrm{RU}} < 28$ outperforms all reference protocols for all the considered values of λ.

In Fig. 8(b), the average delay L is shown as a function of λ. Due to the framed structure of OBV, a higher L was expected compared with CSMA/CA. This is true for light traffic conditions ($\lambda \leqslant 0.5$). For larger values of λ, the rapid increase in the collision probability of CSMA/CA (particularly without RTS/CTS) leads to an increase in L, and OBV becomes preferable. MS-ALOHA always provide the largest delays, particularly when a single slot per OBU is used.

Finally, Fig. 9 shows D_R as a function of δ_{OBU}, for various values of N_{RU}. Three values for the network load $\lambda = 1$, 2, and 10 packets/s, are considered in Fig. 9(a)–(c), respectively. The figure shows that OBV always obtains the highest delivery rate. The difference with the other protocols increases when the network load and the OBU density increase.

C. OBV Versus Reference Protocols in the Highway Scenario

Fig. 10 shows D_R provided by OBV and reference protocols in the highway scenario. Although the density of OBUs is higher in this scenario than in the urban one, results confirm all conclusions already drawn.

Specifically, in Fig. 10(a) D_R varying λ, with $\delta_{\mathrm{OBU}} = 1$, is shown. As can be observed, OBV with $N_{\mathrm{RU}} < 28$ provides the highest throughput. The negative effect of using short values for the CP is also notable: When $T_{\mathrm{CP}} = 0.944$ s (i.e., when $N_{\mathrm{RU}} = 28$), performance is worse than *MS-ALOHA as needed* if $\lambda < 2$ packets/s. Concerning the other protocols, the high OBU density of such scenario causes a performance degradation of CSMA/CA protocols. Although it is not shown here for brevity,

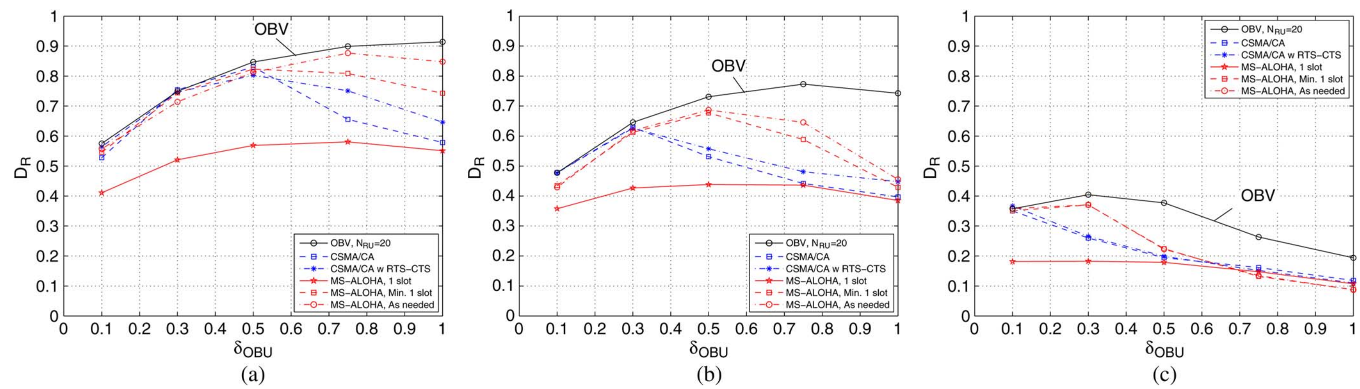

Fig. 9. Urban scenario. Delivery rate versus OBU density. Comparison between OBV, with $N_{\mathrm{RU}} = 20$, and reference protocols. (a) $\lambda = 1$ packets/s. (b) $\lambda = 2$ packets/s. (c) $\lambda = 10$ packets/s.

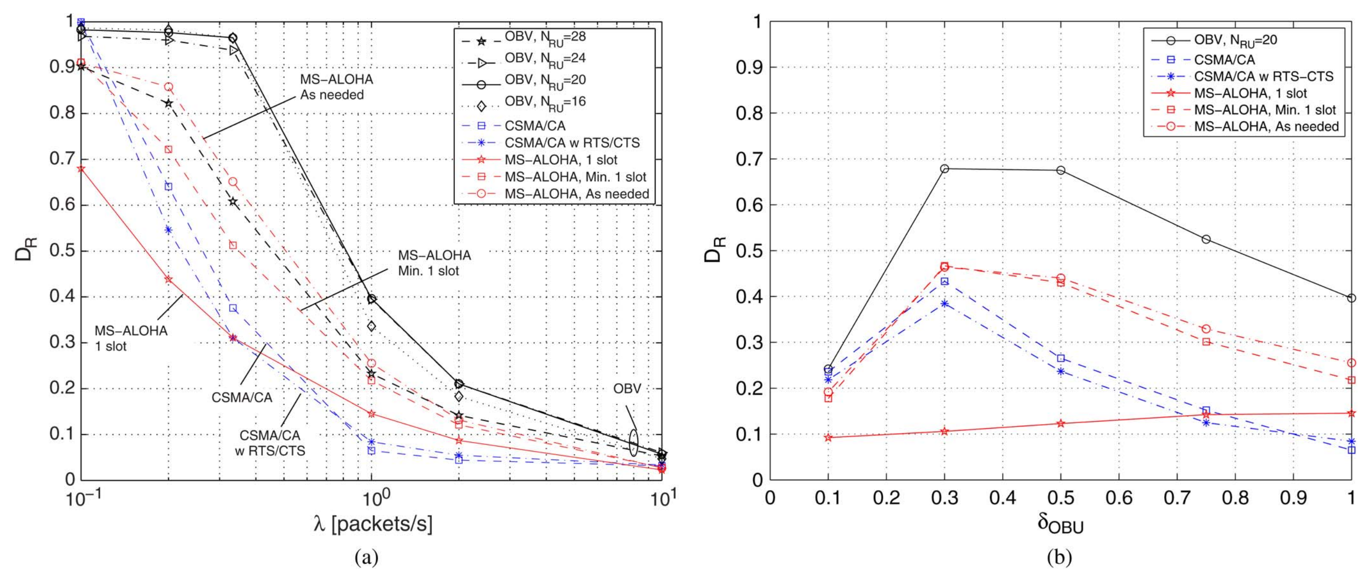

Fig. 10. Highway scenario. Comparison between OBV and reference MAC protocols. (a) D_R versus λ, with $\delta_{\mathrm{OBU}} = 1$. (b) D_R versus δ_{OBU}, with $\lambda = 1$ packets/s.

similar conclusions as in the urban scenario can be drawn for the average delay: MS-ALOHA-based protocols provide the worse performance, CSMA/CA-based protocols give a lower L when the network load is low, and the delay caused by OBV is comparable with that of CSMA/CA for highly loaded network conditions.

Fig. 10(b) shows the delivery rate as a function of δ_{OBU} for $\lambda = 1$ packet/s. OBV outperforms all other protocols when the density of OBUs is high.

VI. Conclusion and Open Issues

In this paper, we have discussed the feasibility of OFDMA as a medium access technique in VANETs, to be adopted in high-throughput service channels. More specifically, we proposed and evaluated a new MAC protocol named OBV, based on OFDMA, with the same configuration of IEEE 802.11p at the PHY layer. The proposed scheme has a frame structure: In each frame, conventional CSMA/CA is employed for the contention-based negotiation phase, whereas OFDMA is adopted during the following contention-free transmission phase.

To evaluate the performance of OBV and compare it with CSMA/CA-based and TDMA-based schemes, a simplified mathematical model has been derived for a three-OBU scheme with two hidden terminals. An investigation has been also carried out in terms of simulations by considering realistic urban and highway scenarios. OBV provides a throughput that is around two times higher than the reference protocols under heavy-load network conditions. The potential drawback of a higher delay of OBV compared with CSMA/CA-based protocols has been quantified, and results show larger delays only under light-load network conditions. When network traffic increases, OBV provides the smallest delays. In addition, OBV always outperforms TDMA-based protocols in normal or dense traffic conditions.

Even if the OBV MAC has proved to significantly increase resource efficiency, there are various aspects that have not been deepened and opened the way for future work.

1) The use of the standard IEEE 802.11p based on CSMA/CA in the negotiation phase might not be the optimum solution, and other protocols might increase the probability that the RR and grant phase successfully concludes.

2) OFDMA benefits from the frequency selectivity of the channel. A further improvement could thus be achieved by optimizing the resource allocation in the frequency domain.
3) The framed structure with requests and grants in the CP allows the receiver to estimate the received power level and suggest the optimal rate to be used in transmission; thus, adaptive modulation and coding could be fully exploited with OBV.
4) With OFDMA, more than one service channel can be used opportunistically at the same time with reduced effort, due to its scalability property.
5) The use of OFDMA at the MAC layer also allows the implementation of the alert message flooding described in [31], which solves the broadcast storm problem that arises when many devices simultaneously contend for the medium to relay the same message: Exploiting the properties of OFDM, all OBUs use the same resources to transmit the same message in a cooperative rather than competitive way, thus increasing reliability in emergency situations.

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