On the End-to-End Delay Analysis for an IEEE 802.11P/WAVE Protocol

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***Abstract* – The use of IEEE 802.11p for supporting intelligent transportation systems (ITS) allows a wide spectrum of applications providing vehicle occupants useful information related to public safety and road efficiency. The Wireless Access for Vehicular Environment (WAVE) standard is specifically tailored for delivering safety and multimedia messages in a highly dynamic vehicular communication environment.**

Such dynamic characteristics along with the delay-critical nature of safety services turn the medium access control protocol (MAC) timings very important. Therefore, it becomes of great interest to analyze a major performance metric, the end-to-end delay.

I. Introduction

Vehicles ubiquity along with the exponential growth of technology, namely wireless communications, led the development of intelligent transportation systems (ITS). The ITS infrastructure should support a variety of new services/applications related with infotainment but also with public safety (e.g., collision avoidance).

Vehicular networks present unique characteristics. They are variable and have highly dynamic scale and network density with rapid topology changes. Due to the relationship between vehicle velocity and human capabilities and limitations, speed is a primary traffic safety issue. Although inattention is the main cause for rear-end accidents, the second most common cause is following too closely [1].

It has been found that on motorway the most preferred headway is around the region of 2s. For example, considering vehicles moving at speeds of 115 km/h (32 m/s) and with an inter-vehicle spacing of 1s (32 m), if the front car starts to brake hard with deceleration of 4 m/s^2, and considering the rear car's driver reaction time is 1,5s, it will cause a collision [2]. The medium access control (MAC) layer plays a major role in delivering safety messages with stringent timing requirements. It is therefore of great interest to analyze a major performance metric such as the end-to-end delay.

With the purpose of supporting the communication requirements of safety and infotainment services in vehicular and ITS environments, in year 1999, at the US, the Federal Communications Commission (FCC) allocated 75 MHz of Dedicated Short Range Communications (DSRC) at 5.850-5.925 GHz frequency band. In August 2008, the Commission of the European Communities decided on the harmonized use of the radio spectrum in the 5.875-5.905 GHz frequency band for safety related ITS applications. Targeting an efficient and standard use of these bands in ITS applications, the IEEE802.11p and the Wireless Access for Vehicular Environments (WAVE) standards (usually named DSRC 5.9 GHz) aim to integrate safety and non-safety services in vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communications. These standards should provide very low latency to support safety real-time applications, operating at speeds up to 200km/h and ranges up to 1000 meters, and, at the same time, non-safety applications providing data rates up to 27Mbps.

The performance of the IEEE 802.11 MAC distributed coordination function (DCF) using CSMA/CA protocol has been studied theoretically in several works. Most provide mathematical models confined to special cases such as single hop networks operating on a saturated assumption, which means that every node in the network has a packet to send at any time. The saturated model restricts the end-to-end delay performance full study since it does not consider the impact of the MAC layer queue. The IEEE 802.11e EDCA (Enhanced Distributed Channel Access) scheme was also subject to performance analysis in several other works.

In this paper, we estimate the end-to-end delay of a specific WAVE MAC protocol, relying in V2V and V2I single-hop communication for timely delivery of safety messages, and compare it with the maximum limit allowable for a specific application.

The rest of this paper is organized in the following way: section II presents some studies made on IEEE 802.11/802.11e MAC performance, section III presents an overview of the DCF used on WAVE MAC layer and its limitations, section IV presents the protocol analysed and the delay model used, section V shows the numerical results obtained and finally section VI presents some conclusions. The work is done with cooperation of BRISA – Autoestradas de Portugal SA, a Portuguese highway concessionary.

II. 802.11 MAC DCF Performance Studies

Bianchi was the pioneer in using a Markov process to model the saturation throughput analytically [3]. Wu et al. extend Bianchi's model including the packet retransmission limit [4]. Others proposed refinements to those models but were all mainly focused on saturation throughput analysis. In [5] Vardakas et al. perform an extensive end-to-end delay analysis, based on Bianchi's model, and including the queuing delay by using the

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M/G/1 queue. Already under any load condition, in [6] Tickoo and Srikdar calculated the overall delay of a packet in a single-hop network by modeling the queue at every node as a G/G/1 queue. In [7], Khalaf and Rubin provide a mathematical model to estimate throughput and end-to-end delay, including queue delay, over single-hop and multihop networks under any loading condition. In [8], Vassis and Kormentzas present an analytical model for delay performance evaluation of IEEE 802.11e EDCA scheme, under finite load conditions for single-hop networks and considering that each station has only one access category index (ACI). The maximum allowable number of retransmissions is not taken into account. In [10], Ho et al. propose an analytical model for delay performance of 802.11e EDCA using two virtual collision handler (VCH) schemes. They extend the model used in [9] to *c* queues for *c* different ACs. Both in [9] and [10] the saturation condition is assumed and they do not take into account the queuing delay. In [11], the associated bounds with packet delivery latency, of 802.11-based V2V protocols for rear-end collision avoidance applications, are precisely quantified. To the best of our knowledge, the end-to-end delay analysis of IEEE 802.11p/P1609.4 MAC protocol, including the specificity of control channel (CCH) and service channel (SCH) usage, under any loading condition, has not been addressed yet.

III. IEEE 802.11P/IEEE P1609.4 MAC DCF Overview and Limitations

The WAVE MAC access method relies on IEEE 802.11 DCF based in CSMA/CA and also on the EDCA mechanism of IEEE 802.11e to support MAC-level quality of service (QoS). To achieve service differentiation, each AC is characterized by its specific contention window (CW) size, arbitration interframe space (AIFS) value, and transmission opportunity (TXOP) limit value, which together determine the backoff procedure. Therefore, a packet from a lower priority queue will wait probabilistically more than that of a higher priority queue before being able to access the medium.

The WAVE standard uses a multi-channel concept which can be used for both safety-related and mere infotainment messages. The spectrum is structured in the upper 5 GHz range and relies into seven 10 MHz bandwidth channels. The band is free but licensed. It uses one CCH – CH 178 – reserved to safety relevant applications and system control and management with high priorities. The other six channels are used as SCHs, mainly supporting the non-safety relevant applications. A global synchronized channel coordination scheme is used as specified in IEEE P1609.4. The channel time is divided into synchronization intervals with fixed length of 100ms, consisting of a CCH and SCH intervals.

Relatively to limitations, although EDCA provides four QoS levels, a station cannot reserve the medium and access it without needing to contend for it. Moreover, there is no distributed admission control algorithm. Therefore, it is not possible to provide QoS guarantees using EDCA, meaning timely delivery of safety messages with real-time requirements. Due to the absence of a contention free period, even though the EDCA priority system increases the probability of certain packets access the wireless channel, there are no guarantees that this will happen before a deadline.

In practice vehicular communications are prone to several aspects that can jeopardize the timely delivery of a safety message. Those aspects are delivery latency (related with contention in the MAC mechanism for single-hop transmission), packet losses (related with wireless channel characteristics and also with the hidden node problem), and finally the driver's reaction time.

IV. The Delay Model and MAC Protocol Studied

A. MAC Protocol

For vehicle safety applications there is a need to use a WAVE-based protocol that can achieve reliable message delivery with time-bounded delay. A variety of protocols have been proposed, mainly relying on vehicular ad-hoc networks, where V2V communication is used to deliver messages. These protocols assume that vehicles are properly equipped and able to "talk" with each other.

However, the 802.11P/WAVE standard was published recently and the large majority of vehicles nowadays are not yet equipped with communication devices. Moreover, the recent economic scenario does not induce large-scale sales even if "equipped" vehicles start being sold now. Therefore, and using the current Road Side Units (RSUs) in the field, V2I communication may seem a possible alternative to deliver safety messages, if vehicles were equipped with the current inexpensive on-board units (OBUs) used for electronic toll. The authors in [13] have also relied in a V2I based solution, where RSUs coordinate vehicles' access to the medium in order to timely deliver safety-critical data.

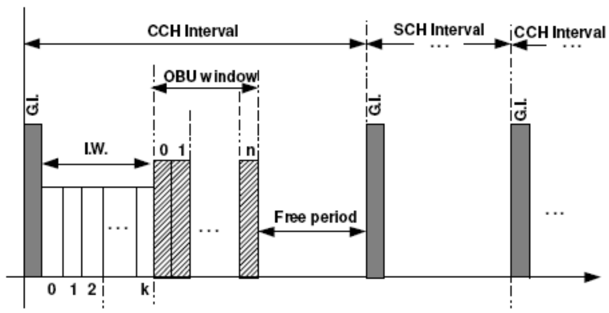

Fig. 1. CCH interval organization ([12]).

In this scenario, the authors in [12], based on [14], propose an infrastructure based solution for safety applications. They assume a total RSU coverage (named RSU zone) in urban freeways or accident-prone areas in highways. The protocol follows a centralized approach where each OBU should register itself when entering the RSU zone (using the CCH interval free period). The RSUs coordinate with each other and schedule the following OBUs transmissions in the CCH, which will occur in the OBU Window as seen in Fig.1. The scheduling is done with trigger messages sent in the Infrastructure Window (I.W.), each containing the OBUs MAC addresses within its range.

In case a safety event occurs, the OBU will transmit the corresponding safety message in its assigned slot. When there is no safety information to send, the OBU transmits its current GPS position and speed.

Our focus in this paper is to evaluate the delivery latency achieved with such proposal after the occurrence of a safety event. It should be noted that the MAC delivery latency (end-to-end delay) is the sum of the media access delay with the queuing delay.

B. Delay Model

The media access delay, t_m, is defined as the interval from the time a packet is elected for transmission by the MAC layer (it is at the head of the queue) until the packet is successfully received by the recipient. Since in this type of protocol contention is avoided, the media access delay is mainly due to the RSU scheduling time and the WAVE synchronization intervals organization. We will assume that RSU scheduling is performed within the current CCH interval which means the OBU may transmit in the following CCH interval. The delay computed here is for the first message transmission (immediately after the vehicle registration within the RSU zone). Due to the protocol design, the following messages will always have a delay less than a synchronization interval (100ms).

Some questions may arise regarding security. However, we will consider that all messages are reliable/credible which means a vehicle may broadcast a safety message in its assigned slot.

Regarding the instant where the safety event takes place within the synchronization interval, various scenarios are possible. We will consider here two, the worst-case and best-case scenarios. In both we consider the I.W. as having a duration of three slots. This is because the coverage area of an RSU is overlapped with the adjacent RSU. Therefore, considering it is important each RSU listens to the trigger messages of two adjacent RSUs, three slots are sufficient. Regarding the assigned slot of the event generator, since this is random, we will assume the middle slot of the total number of slots existent in the OBU window.

Worst-case Scenario

As a worst-case scenario we consider that the vehicle fails to register itself within the free period and the safety event (e.g., hard-braking) takes place immediately at the end of that CCH interval. This means the vehicle should first register itself in order to have an assigned slot in which it can send the safety event message. Therefore, the media access delay for the worst-case, t_{m_wc}, will be:

$$t_{m\_wc} = SCH_{\text{int}} + CCH_{\text{int}} + GI + IW + \tfrac{1}{2} \cdot OBU \tag{1}$$

where SCH_{int} and CCH_{int} are the durations of the SCH and CCH intervals respectively, GI is the guard interval, IW is the infrastructure window duration, and OBU is the duration of the OBU window.

The I.W. duration depends on the number of slots (as explained) and the duration of each slot. Since each slot is used to schedule OBUs transmissions, the duration of each slot will be the necessary duration at a certain bit rate to send the trigger message length (this depends on the number of OBUs under control of the RSU).

The OBU window duration depends on the number of vehicles (one slot for each vehicle) and the duration of each slot. The latter consists of the duration of a specific message at a certain bit rate plus the minimum AIFS for an OBU (which is two according to the standard, corresponding to 2·aSlotTime+SIFS).

Best-case Scenario

A best-case scenario may be that the vehicle is already registered in the RSU zone and the safety event occurs right at the beginning of the CCH interval, which means the vehicle will broadcast the corresponding safety message in the current CCH interval in its assigned slot. Therefore, the media access delay for the best-case, t_{m_bc}, will be:

$$t_{m\_bc} = GI + IW + \tfrac{1}{2} \cdot OBU \tag{2}$$

As it seems more realistic, we will consider alternating access to CCH and SCH as described in the standard. The results would be better in case we considered continuous access to the CCH since the media access delay for the worst-case would be reduced.

Once presented the media access delay we will now focus on the queuing delay. We have already seen that when using EDCA virtual collisions may occur and the collision management mechanism imposes that the queue with highest priority will win the right to try to access the medium. Assuming safety messages are categorized as highest priority messages, it means that a safety event corresponding message will be the one competing for access to the medium if other lower priority messages are current in their queues. Therefore the queuing delay is only due to the other highest priority messages present on queue.

Under finite load conditions the utilization factor of each station is $\rho < 1$ ($\rho = \lambda / \mu$, where λ is the expected packet generation rate and μ is the corresponding expected packet service rate). To simplify we will assume that the generated traffic can be described with a Poisson process. Therefore, we can model each station with an M/G/1 queue with a birth rate of λ

packets/second. The expected number of packets waiting in the highest priority transmitter queue, Q, is given from the Pollaczek-Khintchine mean-value formula [15]:

$$Q = \rho^2 \frac{1 + C_{bi}^2}{2(1-\rho)} \quad (3)$$

where C_{bi} is the coefficient of variation of the media access delay and is equal to σ_{tm}/t_m, where σ_{tm} is the standard deviation of the media access delay. The utilization factor may be rewritten as $\rho = \lambda \cdot t_m$ since the service rate is $1/t_m$. Using Little's theorem, the queuing delay, t_q, can be obtained by dividing (3) by λ.

The inter-vehicle spacing depends on the vehicular mobility model used. Considering the intelligent driver model (IDM) [16] for the equilibrium traffic condition, where drivers tend to keep a velocity-dependent equilibrium gap to the front vehicle, the mean equilibrium gap between two adjacent cars, S, is described by [16]:

$$S(V) = (S_0 + V \cdot \tau)\left[1 - \left(\frac{V}{V_0}\right)^{\delta}\right]^{-\frac{1}{2}} \quad (4)$$

S_0 is the bumper-to-bumper space kept in standing traffic, τ is the safe time headway (1.8s is used), V_0 is the desired velocity when there is no leading vehicle, and δ is the acceleration exponent.

V. NUMERICAL RESULTS AND DISCUSSION

The constant parameters used are listed in Table I. The slot and SIFS time used for AIFS computation is for a 10MHz channel spacing..

TABLE I
CONSTANT PARAMETERS USED

Parameter	Value
RSU transmission range (m)	1500
Average vehicle length (m)	4
Average truck length (m)	10
Truck percentage (%)	8
Highway lanes	6
CCH_{int} (ms)	50
SCH_{int} (ms)	50
GI (ms)	4
aSlotTime (μs)	13
SIFS interval (μs)	32
Payload with security (bytes)	400
S_0 (m)	2
τ (s)	1.8
V_0 (km/h)	125
δ	4

As stated in the previous section, the OBU window duration depends on the number of vehicles (one slot for each vehicle) and the duration of each slot. Using the equation devised in [14], which gives the number of vehicles at the range of a specific RSU, and using the modifications made in [12] to account for the existence of trucks at a certain percentage, the number of vehicles affecting the OBU window duration depends on the first five parameters shown in Table II and also on the inter-vehicle spacing.

A. Media Access Delay

As seen in (1) and (2) the media access delay depends on the I.W. and OBU window durations. Consequently it also depends on the number of vehicles. For various speeds (leading to distinct inter-vehicle spacing from (4)) we have determined the number of vehicles needing a slot assignment from a specific RSU (in some cases not all can be served). Determining the RSU trigger message size (number of vehicles times the MAC address length) for each bit rate admissible in the standard, we have determined the I.W. duration. We have also determined the safety event message duration for each bit rate and consequently the duration of the OBU window.

Taking into account the worst-case scenario described in the previous section and using (1), we have determined the media access delay, t_{m_wc}, as a function of the number of vehicles within the range of a specific RSU, as seen in Fig. 2.

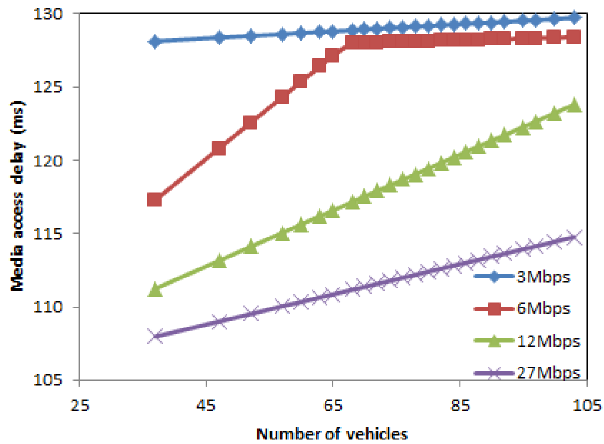

Fig. 2. Worst-case scenario media access delay.

For the best-case scenario and using (2) we have obtained the media access delay, t_{m_bc}, as seen in Fig. 3.

The behavior of media access delay for each bit rate is very similar in both scenarios only varying in terms of absolute values. So, when increasing the number of vehicles the increase on the media access delay will be the same independently of the actual scenario.

As expected, for a certain number of vehicles, as the bit rate increases the media access delay decreases. The almost constant delay observed in the 3Mbps and part of the 6Mbps case, are related to the fact that the OBU window can only serve, in those bit rates, a limited number of vehicles that are within the RSU range. This means we are assuming the event generator is one of the served vehicles and the delay seen is for that case.

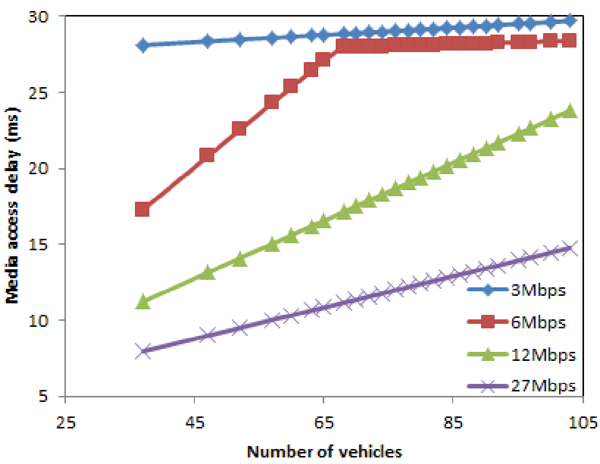

Fig. 3. Best-case scenario media access delay.

With respect to absolute values, for free flow traffic condition (100km/h and 60 vehicles), the worst-case scenario yields a media access delay of 128,7ms at 3Mbps and 110,3ms at 27Mbps. The best-case scenario produces 28,7ms at 3Mbps and 10,3ms at 27Mbps. For congested traffic (10km/h and 100 vehicles), the worst-case scenario yields a media access delay of 129,6ms at 3Mbps and 114,5ms at 27Mbps. The best-case scenario produces 29,6ms at 3Mbps and 14,5ms at 27Mbps.

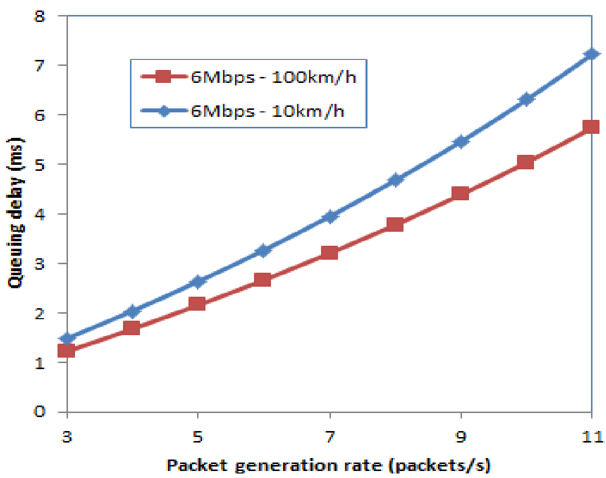

Fig. 4. Best-case scenario queuing delay.

B. Queuing Delay

As seen in (3), the standard deviation of the media access delay is needed to compute the queuing delay. To do so we consider 50 rebroadcasts for the safety event message. This number relates to the message's lifetime (which gives approximately 5 seconds rebroadcasting the message). The first broadcast have a media access delay given by (1) or (2) and the following broadcasts will all have 100ms of media access delay (one synchronization interval) since the OBU slot is already assigned. We have computed the queuing delay for free flow traffic condition (vehicles at 100km/h).

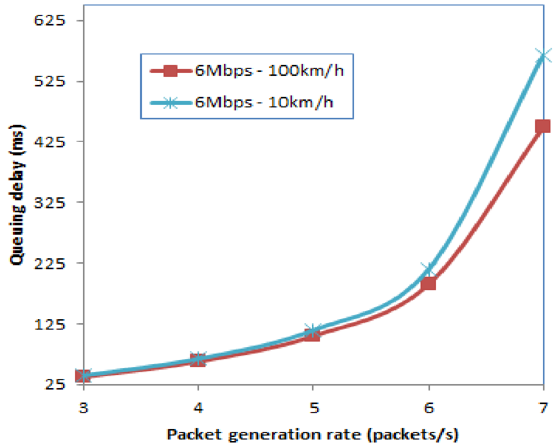

Fig. 5. Worst-case scenario queuing delay.

As seen in Fig. 4 and Fig. 5, the queuing delay is obtained as a function of the packet generation rate, λ. All rebroadcasts (generated "simultaneously" at the time the safety event occurs) are the same safety message repeatedly transmitted. We have used an approximation in considering the packet generation rate is the mean rate of the highest priority queue which includes all those rebroadcasts and other messages from that same queue.

TABLE II
END-TO-END DELAY RESULTS (IN MILLISECONDS)

Scenario / Bit rate ($\lambda = 5$)		Congested (10km/h)			Free-flow (100km/h)		
		t_m	t_q	$t_m + t_q$	t_m	t_q	$t_m + t_q$
Worst-Case	3Mbps	130	119	249	129	116	245
	6Mbps	128	115	243	125	106	231
	12Mbps	123	99	222	116	79	195
	27Mbps	114	77	191	110	68	178
Best-Case	3Mbps	30	2.9	32,9	28	3	31
	6Mbps	28	2,6	30,6	25	2,1	27,1
	12Mbps	23	1,8	24,8	16	1	17
	27Mbps	14	0,9	14,9	10	0,7	10,7

Since the behavior is very similar at the various bit rates, we chose to represent only the 6Mbps at both conditions of congested traffic and free flow (10km/h and 100km/h respectively). The exponential increase observed in the worst-case scenario will also occur in the best-case scenario at a much higher packet generation rate. This is because the media access delay is higher in the worst-case scenario which leads to a lower standard deviation and consequently higher queuing delay at lower packet generation rates. For the worst-case scenario, the traffic condition has a major effect in the queuing delay when the packet generation rate increases over about eight packets/s, with congested traffic causing a major increase in queuing delay.

We can compare the results in Table II with the latency upper bound derived in [11] since it takes into account the vehicles' motion equations, and is a function of vehicles' emergency deceleration, the gap between vehicles, and the driver's reaction time (assumed 1s). Therefore, their approach may be generalized no matter if the safety message is delivered through single-hop V2V communication or using also V2I communication. In the first case the latency is mainly caused by the MAC contention mechanism, whereas in the latter the latency is mainly caused by RSUs coordination and scheduling of safety message delivery, since it should eliminate contention between vehicles.

VI. CONCLUSIONS

Regarding IEEE 802.11p/P1609.4 MAC utilization and the specificity of CCH and SCH usage, the assumed requirement of using the CCH for safety information dissemination can strongly affect the end-to-end delay depending on the scenario considered (i.e., at what instant have the safety event occurred).

By observing the previous section figures we can conclude that if the latency achieved is not admissible an eventual solution may be to work at a higher bit rate thus reducing the media access delay. When falling in the best-case scenario a higher packet generation rate may be supported without increasing the queuing delay exponentially and keeping the total latency small. The traffic condition has a higher impact on the media access delay at lower bit rates, and in the worst-case scenario a greater impact at higher packet generation rates.

The upper bound end-to-end delay in order rear-end collision can be avoided after a sudden brake, derived in [11] for the asphalt road (most stringent), at 10km/h is about 300ms whereas at 100km/h the upper bound is about 2,83s (lower velocities corresponding to congested traffic lead to smaller inter-vehicle spacing, and consequently the delay should be small enough to allow reaction by the following vehicle). Comparing these values with the results shown in Table II, we can conclude that the devised protocol may perform well in safety applications such as sudden brake rear-end collision.

Acknowledgments

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