

# Throughput Differentiation for TCP Uplink Traffic in IEEE 802.11e Wireless LANs

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**Abstract**—We investigate a model to achieve throughput differentiation and efficient channel utilization for TCP uplink traffic over IEEE 802.11e's Enhanced Distributed Channel Access (EDCA) mechanism, when TCP acknowledgement packets are given higher priority for accessing the wireless channel compared to data packets. The proposed model can be used to tune the minimum contention window of EDCA to support efficient throughput differentiation according to a weight parameter, while taking into account factors such as the CSMA/CA and RTS/CTS procedure and different physical layer transmission rates. Simulation results validate the accuracy of the proposed model, and show its effectiveness in supporting weighted throughput differentiation.

**Keywords:** contention-based access, service differentiation, channel efficiency

## I. INTRODUCTION

Wireless LANs (WLANs) will be an important access technology in future broadband networks, as suggested by the significant increase of enterprise wireless LANs, wireless hotspots, and metropolitan wireless mesh networks based on IEEE 802.11. The 802.11b standard can support transmission rates up to 11 Mbps, whereas the newer standards 802.11a/g support transmission rates up to 54 Mbps. Hence, the capacity of wireless LANs is at least one order of magnitude smaller than the capacity typically available in wired networks. Moreover, there is a limited ability to increase the capacity of wireless networks, since it is limited by the available spectrum. The above necessitate the efficient utilization of the wireless channel. Additionally, applications have different throughput requirements and the dominating transport protocol in the Internet is TCP, hence there is a need to support service differentiation for TCP over IEEE 802.11.

In this paper we adapt and evaluate for TCP uplink traffic the resource control model for IEEE 802.11e's Enhanced Distributed Channel Access (EDCA) mechanism presented in [10]. In order to obtain a tractable analytical expression for the throughput in the case of TCP uplink traffic, similar to [7], we assume that TCP acknowledgements are transmitted with a higher priority compared to TCP data packets; hence, the possibility of collisions involving TCP ACK packets is negligible. The proposed model can be used to tune the minimum

contention window of EDCA in order to support throughput differentiation according to a weight factor, while achieving efficient utilization of the wireless channel. Important features of the model is that it captures the performance of TCP uplink traffic over 802.11e, while taking into account the specific characteristics and operation of 802.11e's contention-based EDCA mechanism such as the CSMA/CA and RTS/CTS procedures and the physical layer transmission rate, which can be different for different wireless stations.

Our work differs from [7], which also considers TCP while giving higher priority to TCP ACK packets, in that we focus on throughput differentiation and maximizing the wireless channel utilization, and from [9], [1], which also consider weighted differentiation, in that we focus on TCP uplink traffic, and our model is more general in that it considers the case of wireless stations with different physical layer transmission rates.

## II. IEEE 802.11E'S EDCA AND TCP

In IEEE 802.11, access to the shared wireless channel is controlled through two MAC layer mechanisms: polling-based PCF (Point Coordination Function) and contention-based DCF (Distributed Coordination Function). DCF is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). As in Ethernet's CDMA/CD, according to CSMA/CA, prior to a frame transmission the wireless channel must be sensed idle for a time interval called interframe spacing (IFS), which can be different for different frame types; hence, for data frames the interval is a DCF-IFS (DIFS), and for acknowledgements it is a short IFS (SIFS).

The RTS/CTS procedure is used to avoid the hidden node problem, which can occur when two stations that are not within the range of each other transmit at the same time. According to the RTS/CTS procedure, before transmitting a data frame, a station transmits a special frame called request to send (RTS), after sensing that the wireless channel is idle for time DIFS. The destination, upon receiving an RTS frame responds with a clear to send (CTS) frame. After receiving the CTS frame, the sending station can send the data frame. Using the above procedure the hidden node problem is avoided, since all stations within the range of the destination will receive the CTS frame, independently of whether they are in the range

of the other senders with which they can potentially collide, hence will defer their transmission.

In wireless networks, unlike in Ethernet LANs, collision detection is not possible or is too costly. For this reason the DCF mechanism uses collision avoidance: Before initiating the transmission of a frame, the station selects a random backoff period from the interval  $[0, CW - 1]$ , where  $CW$  is referred to as contention window. The station waits for the channel to be idle for a total time equal to this backoff period, after which it senses the channel to see if it is idle for a DIFS interval, in which case it can transmit a data frame, when the basic CSMA/CA procedure is used, or an RTS frame, when the RTS/CTS procedure is used.  $CW$  has an initial value  $CW_{min}$ , and is doubled when a collision occurs, up to the maximum value  $CW_{max}$ . When a frame is successfully transmitted,  $CW$  is reset to  $CW_{min}$ .

IEEE 802.11e is an upcoming version of the IEEE 802.11 standard that addresses the issue of QoS support in wireless LANs. The MAC protocol of IEEE 802.11e is the Hybrid Co-ordination Function (HCF), which supports both contention-based and controlled channel access [4], and coexists with the basic DCF and PCF mechanisms for backward compatibility. The contention-based access of HCF is based on the Enhanced Distributed Channel Access (EDCA) mechanism, which is an extension of the DCF mechanism that enables distributed differentiated access to the wireless channel with the support of multiple access categories (ACs). A higher priority access category has a smaller minimum contention window  $CW_{min}$ , thus giving it a higher probability to access the channel. Additionally, different access categories can have different values for the maximum contention window  $CW_{max}$  and the interframe spacing interval (IFS), which is now called Arbitration IFS (AIFS). It is important to note that although the IEEE 802.11e standard defines a number of parameters that can be used to achieve service differentiation, it does not define how these parameters should depend on the network load and traffic characteristics in order to efficiently utilize the shared wireless channel.

Studies have shown that different values for  $CW_{min}$  can provide differentiation in terms of throughput, e.g. see [8] and the references therein. On the other hand, different values for  $CW_{max}$  lead to different service only in cases of increased collisions. Moreover, different values for AIFS are effective for supporting different priorities in accessing the wireless channel. Motivated by these results, in this paper we investigate models that consider the minimum contention window  $CW_{min}$  for controlling access to the shared wireless channel.

#### A. Throughput model for TCP over EDCA

In this section we discuss an analytical model that gives the throughput of a station in an IEEE 802.11 wireless LAN using the EDCA mechanism. In order to obtain a tractable analytical expression for the throughput of TCP traffic, similar to [7], we assume that TCP acknowledgements flowing from the access point to the wireless stations have a higher priority for accessing the wireless channel. Hence, contention occurs only in the

uplink direction, among TCP data packets. As discussed in [7], this yields fairer bandwidth sharing among the different TCP flows. Higher priority is achieved by transmitting TCP ACKs with  $CW_{min} = 1$ , i.e. TCP ACKs packets are transmitted immediately once the channel is sensed idle<sup>1</sup>.

Several analytical studies have approximated the congestion avoidance procedure of IEEE 802.11 with a p-persistent model [3], [9]. In a p-persistent model, the probability that a station tries to transmit in a time slot is  $p$ , and is independent of the success or failure of previous transmission attempts. It has been shown that the p-persistent model closely approximates the throughput of the actual congestion avoidance procedure of 802.11, when the average backoff interval is the same [3].

In particular, if  $E[CW]$  is the average contention window, then the approximate p-persistent model has a transmission probability  $p$  given by [3]

$$p = \frac{2}{E[CW] + 1}.$$

If we assume that the probability of a frame being involved in more than one collision is very small, then we have the approximation  $E[CW] \approx CW_{min}$  [9]. In IEEE 802.11e, different wireless stations can have a different minimum contention window, hence using the same arguments as above [9], the corresponding transmission probability of station  $i$  in the p-persistent model is

$$p_i = \frac{2}{CW_{min,i} + 1}. \quad (1)$$

Hence, we can estimate the throughput for a given set of stations with different values of the minimum contention window, by approximating it with the corresponding p-persistent model, where the transmission probability of a station is given by the above relation.

The MAC operation of IEEE 802.11 can be viewed in time as involving three different types of time intervals: a successful transmission interval, a collision interval, and an idle time interval. We denote the length of each interval type as  $T^{suc}$ ,  $T^{col}$ , and  $T^{idl}$ , respectively. The duration of each time interval depends on the physical layer encoding and the MAC layer operations. In particular, we have the following:

$T^{suc}$ : For the basic CSMA/CA operation in 802.11b, we have the following<sup>2</sup>:

$$T^{suc} = 2T_{PHY} + T_{SIFS} + \frac{8(34 + L)}{R} + T_{ACK} + T_{DIFS},$$

where  $L$  is the frame length, 34 bytes is the MAC overhead,  $R$  is the transmission rate, and  $T_{PHY}$ ,  $T_{SIFS}$ ,  $T_{DIFS}$ ,  $T_{ACK}$  are the durations (in time units) of the physical layer overhead, the SIFS interval, the DIFS interval, and the ACK transmission time, respectively. For TCP traffic, under the assumption that TCP ACKs are transmitted with higher probability compared to TCP data packets, the duration of a successful TCP packet

<sup>1</sup>For simplicity, we assume that the IFS interval is the same for data and TCP ACK packets.

<sup>2</sup>We assume the propagation delay is very small, hence do not consider it.

transmission will involve the transmission times for the data packet, the TCP acknowledgement packet, and the two MAC layer acknowledgement. Hence, we have

$$T^{TCP,suc} = 4T_{PHY} + 2T_{SIFS} + \frac{8(34+L)}{R} + \frac{8(34+L_{TCPACK})}{R} + 2T_{ACK} + 2T_{DIFS},$$

where  $L_{TCPACK} = 40$  bytes is the length of the TCP ACK packet.

In 802.11b, ACK, RTS, and CTS frames are transmitted at 1 Mbps, hence their transmission times are independent of the rate  $R$ . For RTS/CTS we have

$$T^{suc,RTS/CTS} = 4T_{PHY} + 3T_{SIFS} + \frac{8(34+L)}{R} + T_{RTS} + T_{CTS} + T_{ACK} + T_{DIFS},$$

where  $T_{RTS}$ ,  $T_{CTS}$  is the duration of an RTS, CTS frame transmission, respectively.

$T^{col}$ : For basic CSMA/CA we have

$$T^{col} = T_{PHY} + \frac{8(34+L)}{R} + T_{DIFS}.$$

For RTS/CTS the collision interval is

$$T^{col,RTS/CTS} = T_{PHY} + T_{RTS} + T_{DIFS}.$$

Note that the above expressions for the collision interval also hold in the case of TCP traffic, because collisions will be due to the initial transmission of TCP data packets since we have assumed that TCP ACK packets are transmitted with higher probability hence the possibility of them being involved in collisions can be assumed to be very small.

$T^{idl}$ : This is equal to one time slot, whose default value for IEEE 802.11b and 802.11a is  $20 \mu s$  and  $9 \mu s$ , respectively.

Time can be viewed as a sequence of intervals of the above types. The average throughput for station  $i$ , considering a renewal assumption, can be expressed as the ratio of the average data transmitted by that station in one time interval over the average duration of a time interval [2], [3], [9].

$$x_i = \frac{E[X_i]}{E[T]},$$

from which we find that, when all stations have the same transmission rate, the average throughput  $x_i$  for station  $i$  is

$$x_i = \frac{p_i(1-P_{-i})L}{\sum_k p_k(1-P_{-k})T^{suc} + [P - \sum_k p_k(1-P_{-k})]T^{col} + 1 - P} \quad (2)$$

where  $P_{-i} = \sum_{j \neq i} p_j$ . Note that the above expression is valid for all versions of 802.11, and for both UDP and TCP traffic (assuming we have given priority to TCP ACKs, as discussed in the beginning of the section), provided all stations have the same transmission rate. The specific version of 802.11, and whether the CSMA/CA or RTS/CTS procedure and TCP or UDP traffic is considered, will determine the values of  $T^{suc}$  and  $T^{col}$ , which in the above expression for the average throughput we have taken to be normalized to the duration of the idle interval.

The above throughput expression is valid under saturation conditions, where a packet is always available for transmission

across the wireless channel. In the case of TCP, this occurs when TCP's congestion control algorithm can inject packets at a higher rate than the 802.11 MAC can transmit across the wireless channel; this is the case when the wireless link is the bottleneck, as our simulation results in Section IV demonstrate.

As discussed previously, in 802.11b with the RTS/CTS procedure, the transmission rate does not affect the collision interval, since the latter involves RTS frames which are always transmitted at the basic rate (1 Mbps). Hence, for 802.11b with the RTS/CTS procedure, when different stations have a different transmission rate, the average throughput  $x_i$  is

$$x_i = \frac{p_i(1-P_{-i})L}{\sum_k p_k(1-P_{-k})T_k^{suc} + [P - \sum_k p_k(1-P_{-k})]T^{col} + 1 - P} \quad (3)$$

The last expression for the throughput of a wireless station captures a well-known property of 802.11 networks [5]: a station with a small transmission rate leads to decreased throughput not only for itself, but for all other wireless stations in the same network, independently of their transmission rate; this is because a small transmission rate for some station increases the denominator in (3) for all stations  $i$ .

Next we consider the case where the collision interval also depends on the transmission rate. If we assume that the probability for three or more frames to collide is negligible, then the average throughput  $x_i$  is

$$x_i = \frac{p_i(1-P_{-i})L}{\sum_k p_k(1-P_{-k})T_k^{suc} + \sum_k \sum_{j \neq k} p_k p_j \max\{T_k^{col}, T_j^{col}\} + 1 - P},$$

where  $T_k^{col}$  is the collision interval for station  $k$ . In the remainder of the paper we consider only the throughput expressions (2) and (3).

### III. WEIGHTED THROUGHPUT DIFFERENTIATION

In this section, based on the throughput model in the previous section, we apply the economic modelling framework presented in [10] to TCP uplink traffic, for achieving weighted throughput differentiation and efficient wireless channel utilization. To achieve proportional resource sharing we can assume that each user  $i$ 's valuation for his average throughput  $x_i$  is given by the following logarithmic utility function [6]

$$U_i(x_i) = w_i \log x_i, \quad (4)$$

where  $w_i$  is the weight or willingness-to-pay factor.

Consider the problem of maximizing the aggregate utility (social welfare), in a wireless network with a set of users  $N$

$$\begin{aligned} & \text{maximize} && \sum_i U_i(x_i) \\ & \text{over} && \{p_i \geq 0, i \in N\}. \end{aligned} \quad (5)$$

If  $U_i(\cdot)$  is differentiable and strictly concave, then the necessary conditions for the maximization in (5) are

$$\frac{\partial \sum_i U_i(x_i)}{\partial p_i} = \frac{\partial U_i(x_i)}{\partial p_i} + \sum_{j \neq i} \frac{\partial U_j(x_j)}{\partial p_i} = 0, \quad (6)$$

for  $i \in N$ .

If all stations have the same physical layer transmission rate, then the throughput for a wireless station is given by (2). Substituting this equation in (6), and after computing the partial derivative  $\frac{\partial U_i(x_i)}{\partial p_i}$ , we find that the necessary conditions for the global optimum are approximately

$$\frac{\partial U_i(x_i)}{\partial p_i} = L \frac{(1-P)^2 T^{suc} + P(2-P)T^{col}}{E[T]^2} \sum_j U'_j p_j, \quad (7)$$

for  $i \in N$ , where  $P = \sum_j p_j$ . If  $p_i \ll P$ , which will hold when there is a large number of stations,  $E[T]$  can be approximated by

$$E[T] = P(1-P)T^{suc} + P^2 T^{col} + 1 - P.$$

When all users have the same utility function, from (7) we find that the necessary condition for optimality is

$$P = \frac{(1-P)E[T]}{(1-P)^2 T^{suc} + P(2-P)T^{col}},$$

hence the optimal aggregate transmission probability  $P$  is independent of the utility function. Note that this transmission probability also maximizes the aggregate throughput over the wireless channel. The above equation can be solved analytically, in which case we find

$$P = \frac{\sqrt{T^{col}} - 1}{T^{col} - 1}. \quad (8)$$

The last equation suggests the following interesting result: For a large number of stations, all having the same utility, when the aggregate transmission probability is much smaller than one, then the optimal aggregate transmission probability that maximizes the economic efficiency of the wireless channel is independent of the specific utility function and the successful transmission interval, and depends only on the collision interval normalized to the idle time slot.

The optimal transmission probability for a station  $i$  with the utility (4) is given by (see [10] for the detailed derivation)

$$p_i = \frac{w_i}{\sum_j w_j} P, \quad (9)$$

which indicates that the aggregate transmission probability is shared in proportion to the weights of the wireless stations. The optimal minimum contention window  $CW_{min,i}$  can be computed from (1). The above model for the case of identical transmission rates is similar to the one presented in [1], but here we consider a different approximation, which yields simpler expressions.

If different stations have different physical layer transmission rates, which affect only the duration of the successful transmission interval  $T_i^{suc}$ , in which case the throughput of a station is given by (3), then the optimal transmission probability is

$$p_i = \frac{w_i}{\sum_j w_j} \frac{(1-P)E[T]}{(1-P)^2 T_i^{suc} + P(2-P)T^{col}}.$$

The above expression, together with  $P = \sum p_j$ , can be solved arithmetically. As before, the optimal minimum contention window  $CW_{min,i}$  can then be computed from (1).

## IV. EXPERIMENTS

In this section we present simulation results that demonstrate and evaluate the models presented in the previous sections. The simulation results were obtained using the ns-2 simulator, with the module<sup>3</sup> documented in [11] for implementing the EDCA mechanism. The simulation experiments considered TCP traffic with packet size 1040 bytes, which includes the TCP/IP overhead, while the size of the TCP ACK packets is 40 bytes. As discussed in Section II-A, TCP acknowledgements are given higher priority compared to data packets by setting  $CW_{min} = 1$ . The parameters of IEEE 802.11b required to compute the intervals  $T^{suc}$ ,  $T^{col}$ , and  $T^{idl}$  are shown in Table I. The results we present are the average of 6 runs, each for duration 400 seconds.

Figure 1 compares for IEEE 802.11b<sup>4</sup> with CSMA/CA, and in the case all stations have the same transmission rate, the aggregate throughput estimated from (2) with the value found using simulation. The figure also contains the throughput according to the Bianchi model [2], which considers a more accurate approximation for the backoff mechanism. Observe that the analytical results follow the simulation results very well. Most importantly, the simple p-persistent model we consider in this paper can accurately estimate the optimal minimum contention window. Additionally, from (8), (9), and (1) we find that the optimal minimum contention window is 161, which is very close to the value 128 which yields the maximum throughput according to the simulation (note that the simulation results are for discrete values of  $CW_{min} = 2^k$  for  $k = 3 \dots 10$ ). The results shown in Figure 1 are for a network topology that includes a wireless link and a wired link with propagation delay 2 ms. However, experiments with different propagation delays show that the throughput remains the same: For propagation delay 50 ms and 200 ms the throughput is 3.93 Mbps and 3.94 Mbps, respectively; these results agree with the findings of [7]. These results further confirm that the simple p-persistent model, with the successful transmission interval defined as discussed in Section II-A, can be used to accurately estimate the optimal minimum contention window.

Figure 1 compares the analytical and simulation results in a mixed scenario case, where we have 2 hi priority and 8 low priority TCP flows with weights  $w_{hi}/w_{low} = 4$ . As before we observe that the analytical model can accurately estimate the optimal minimum contention window. Moreover, from (8), (9),

<sup>3</sup>An IEEE 802.11e EDCA and CFB simulation model for ns-2, [http://www.tkn.tu-berlin.de/research/802.11e\\_ns2/](http://www.tkn.tu-berlin.de/research/802.11e_ns2/)

<sup>4</sup>For the analytical results in Figure 1 we have considered 28 bytes MAC overhead, since this is the size used in ns-2.

TABLE I  
PARAMETERS OF IEEE 802.11B

Parameter	Value (in $\mu$ s)
Slot Time	20
$T_{DIFS}$ , $T_{SIFS}$	50, 10
$T_{PHY}$	192
$T_{ACK} = T_{CTS}$ , $T_{RTS}$	112, 160

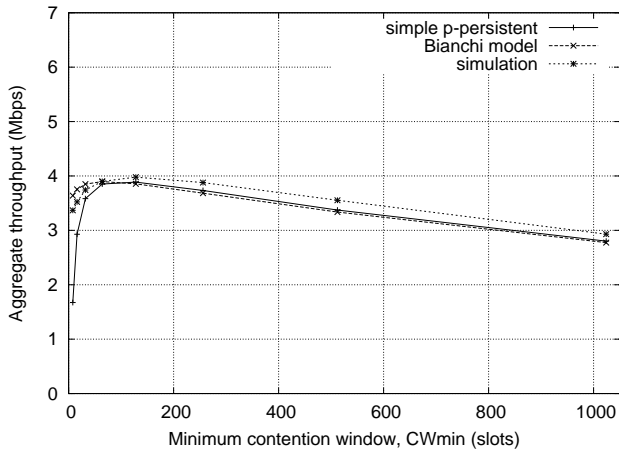


Fig. 1. Simulation and analytical results for 802.11b and CSMA/CA. 10 TCP flows.

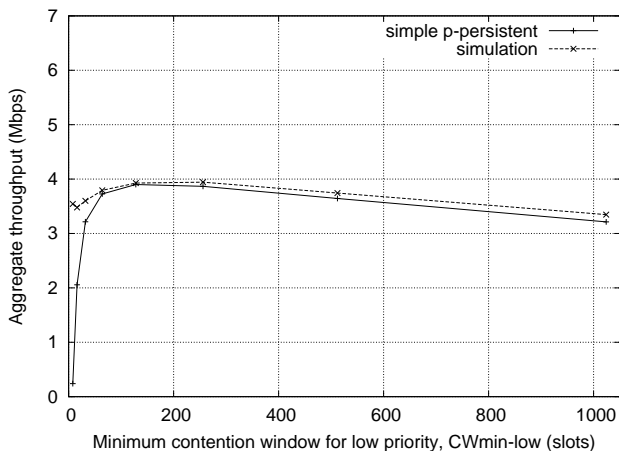


Fig. 2. Simulation and analytical results for 802.11b and CSMA/CA in the case of 2 hi priority and 8 low priority TCP flows with weights  $w_{hi}/w_{low} = 4$ .

and (1) we find that the optimal transmission probability for the low priority flow each station is 226, which is very close to the value 256 that yields the maximum throughput according to the simulation.

Figure 3 shows that in the case of two classes of TCP flows with different weights, the ratio of throughput is equal to the inverse ratio of minimum contention window values<sup>5</sup> when TCP acknowledgements are transmitted with higher probability. On the other hand, this is not the case when TCP acknowledgements are transmitted using the same minimum contention window as data packets. Indeed, in the latter case the ratio of throughput is smaller than the inverse ratio of  $CW_{min}$  values; this can be attributed to the fact that in this case, a higher  $CW_{min}$  results in a TCP flow having a smaller probability of transmitting both a data and an acknowledgment packet. The results in Figure 3 show that

<sup>5</sup>Note that when  $CW_{min}$  obtains a large value, typically larger than 16 as in our case, from (1) and (2) we have that the ratio of throughput for flows belonging to the two classes is inversely proportional to the ratio of  $CW_{min}$  values.

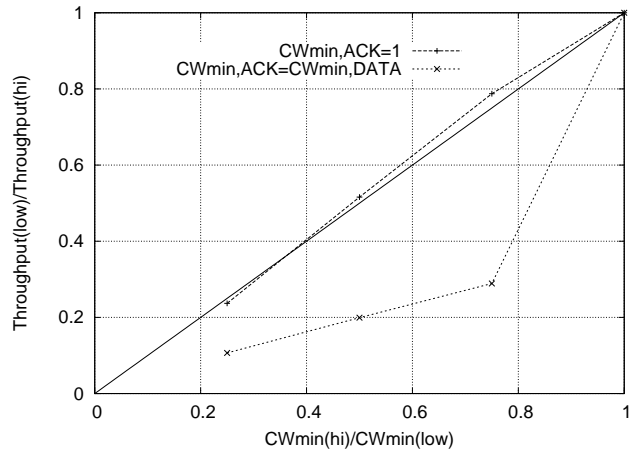


Fig. 3. Ratio of throughput as a function of ratio of minimum contention window values, in the case of 2 hi and 8 low priority TCP flows.

giving TCP acknowledgments higher priority enables more effective support for service differentiation.

## V. CONCLUSIONS

We investigate the application of economic modelling to achieve throughput differentiation and efficient channel utilization for TCP uplink traffic over IEEE 802.11e's Enhanced Distributed Channel Access (EDCA) mechanism, when TCP acknowledgement packets are given higher priority for accessing the wireless channel compared to data packets. The proposed model can be used to tune the minimum contention window of EDCA to support weighted throughput differentiation, while maximizing the wireless channel utilization.

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