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A Novel Performance Model for Distributed Prioritized MAC Protocols

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***Abstract*—Distributed prioritized channel access mechanisms have been adopted by the IEEE 802.11e enhanced distributed channel access (EDCA) and the Multiband OFDM Alliance prioritized channel access (PCA) to support service differentiation. In this paper, we propose a novel analytical model for performance study of such mechanisms. The proposed model gives the average frame service time first and then the per station and network normalized throughput, which makes it applicable to both saturated and unsaturated stations. Furthermore, the model is especially helpful in understanding the different effects of the same prioritizing mechanisms in saturated and unsaturated conditions. To the best of our knowledge, there is no similar work reported in the open literature. The accuracy of the analytical model is demonstrated by extensive simulation.**

I. INTRODUCTION

The IEEE 802.11e amendment [1] to the legacy IEEE 802.11 standard was released recently, aiming to enhance the Quality-of-Service (QoS) provisioning demanded by multimedia services in WLANs. In this standard, the newly defined enhanced distributed channel access (EDCA) supports service differentiation mainly by distributed prioritized channel access among different access categories (ACs) with three AC-dependent parameters: arbitrary interframe space (AIFS), contention window (CW), and transmission opportunity (TXOP). Similar approaches have also been adopted by Multiband OFDM Alliance (MBOA) in its contention based medium access protocol called prioritized channel access (PCA) [2] for emerging ultra-wideband wireless personal area networks (WPANs).

In the literature, two main techniques have been used to analyze the performance of these service differentiation mechanisms. The *discrete time Markov chain* widely used in modeling the DCF has been extended to study the performance of EDCA in [3]–[5] and PCA in [6]. The other one is the *mean value analysis*, which is applied in [7] to derive the network saturation throughput. In [8], the station transmission probabilities are obtained from both mean value analysis and multiple two-dimension Markov chain analysis; and the network throughput is derived from the channel's viewpoint. However, all the analytical models above are for the saturation case and cannot be easily extended to analyze unsaturated stations, which is usually the case in practical multimedia services. The common procedure in these models is that the network saturation throughput is obtained first, usually from the analysis of a typical transmission in the network. Then the per station saturation throughput is derived according to the proportional sharing of network throughput among the stations. Finally, the average frame service time is given as the reciprocal of the per station throughput. However, the last step cannot be applied to unsaturated stations, as will be shown in Section III-C. Therefore, even the per station throughput is known (same as the given incoming traffic load), it is very difficult, if not impossible, to obtain the frame service time with those models.

Recently, the analysis of EDCA with unsaturated stations has been reported in [9] and its follow-up series, which extend the three-dimensional Markov model [5] for saturated stations by adding a set of states with no frame to transmit. The frame service time for low priority stations is underestimated due to the overly simplified calculation of blocking delay in the AIFS periods caused by higher priority stations. Moreover, only "extreme non-saturation condition" is considered in the service time analysis for unsaturated stations, which leads to a seriously flawed estimation of the key parameter (queue utilization factor) of the model and further undermines its accuracy.

In this paper, we propose a novel analytical model for EDCA-like service differentiation MAC protocols for both saturated and unsaturated stations. We model the backoff and channel access behavior of a tagged station in each class based on the theory of renewal processes, and obtain the average frame service time for each class with the analysis of the "pre-backoff waiting" periods of low priority stations. Saturation throughput of individual station is then derived according to the fact that only one successful frame transmission exists in a frame service time period, on average. The wide applicability of the model enables us to understand the different effects of the same prioritizing mechanisms in saturated and unsaturated conditions. In addition, the analysis of all the three main service differentiation mechanisms are naturally integrated into this model. To the best of our knowledge, there is no similar work reported in the open literature.

The remainder of the paper is organized as follows. Section II gives a brief review of the distributed prioritized channel access in EDCA and PCA. Taking a network with two access classes as an example, we present the proposed analytical model in Section III. Analytical results are compared with simulation results in Section IV to assess analytical accuracy; the impact of the key MAC parameters on the protocol performance is also discussed. Concluding remarks are given in Section V.

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II. DISTRIBUTED PRIORITIZED CHANNEL ACCESS

The prioritized CSMA/CA-based MAC that has been adopted in IEEE 802.11e EDCA and emerging MBOA PCA is considered in this paper. Only the distributed prioritized channel access mechanisms are reviewed below. Details of the protocols can be found in [1], [2], respectively.

User traffic is first differentiated into multiple ACs, such as voice, video, best-effort and background. Each station regulates its frame transmission using the contention parameters associated with each AC. When a station has a frame at the MAC sublayer buffer, it will first sense the channel. If the channel is busy, it performs the backoff procedure by first setting the backoff counter to an integer sampled from the minimum CW size. Therefore the first differentiation mechanism is to assign higher priority ACs with a smaller value of minimum CW size such that higher priority ACs statistically spend less time on backoff. After the channel becomes idle for AIFS, the station can count down the backoff counter at the beginning of each idle slot and also the first slot of a channel busy period. Since the higher priority ACs are assigned with smaller value AIFS, they obtain higher chances to access the channel than low priority ACs. Fig. 1 shows an example of four ACs, where AC_1 has the highest priority. To illustrate the effect of different AIFS lengths, the time between two busy period except $AIFS_1$ is divided into four contention zones, $Z_i, i = 1, 2, 3, 4$. In Z_1, only AC_1 stations are allowed to contend for channel access, while in Z_2 the contentions are between AC_1 and AC_2, i.e., contentions in Z_i involve $AC_j, j \leq i$. Consequently, each AC encounters different contentions in its allowable contention zones. After one station succeeds in contending for channel access, it can transmit for a duration up to the TXOP. Different TXOP durations can be assigned to different ACs to further differentiate the service.

III. THE ANALYTICAL MODEL

In this section, we present the proposed analytical model for the mean frame service time and the normalized throughput of a station and the network. We assume that the probability a station initiates transmission in a given backoff slot is constant in all its backoff slots [3], [8]. Since the channel access procedure of the tagged station regenerates itself for each new MAC frame, the complete service periods for MAC frames form renewal cycles in the renewal process. The average length of the renewal cycle is thus the average frame service time. In addition, the per station saturation normalized throughput is just the ratio of the transmission time of the frame payload to the frame service time, because there is only one successful frame transmission in a cycle. The main task of the model is thus to obtain the average frame service times for frames from each class.

The advantage of developing the model from the aforementioned perspective is that it is a unified approach for both saturated and unsaturated stations. To illustrate the essence of the model, the analysis for a network with saturated stations is presented first, followed by the analysis of unsaturated stations. Due to space limit, we only discuss the detailed analysis for a network with two access classes. However, the proposed model is readily applicable to more general cases with more access classes.

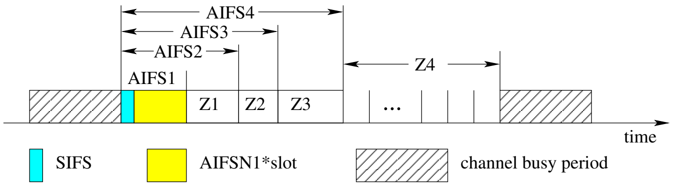

Fig. 1. An illustration of prioritized channel access for different ACs

A. The Network Model

In the following, a network with two classes of saturated stations (N_i stations in $AC_i, i = 1, 2$) is considered first. Unsaturated stations are analyzed in Section III-C. Without loss of generality, let AC_1 stations have high priority and AC_2 stations have low priority in accessing the channel. All the stations are within the same transmission range of one another so there are no hidden terminals in the network. Time is discretized into *generic* slots, which may have different lengths Δ, T_s and T_c corresponding to the different channel status of idle, successful transmission and collisions, respectively. In addition, all the stations are synchronized and they can correctly sense the channel status at the beginning of the slots. Ideal wireless channel without transmission error is assumed so that all transmitted frames may be lost only due to collisions caused by simultaneous transmissions from multiple stations[1]. For simplicity, all MAC frames are assumed to have the same fixed length. The case of different frame lengths (and thus the analysis of TXOP) can be incorporated in our model following the work in [11].

B. The Basic Analysis

We derive two key probabilities first, then proceed to the MAC performance metrics.

1) Station Transmitting Probability and Frame Collision Probability: According to the renewal reward theorem, in a randomly chosen slot, the transmitting probability τ_i of an AC_i station can be obtained as the average reward during the renewal cycle, given by [11], [12]

$$\tau_i = \frac{E[R_i]}{E[R_i] + E[B_i]}, \quad i = 1, 2, \tag{1}$$

where $E[R_i]$ is the average number of transmission trials for a frame and $E[B_i]$ is the average number of total backoff slots experience by the frame. Assuming an average collision probability of P_i for the frames of AC_i stations, R_i follows a truncated geometric distribution and $E[R_i]$ is give by

$$E[R_i] = \sum_{j=0}^{m-1} P_i^j, \quad i = 1, 2, \tag{2}$$

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[1] Imperfect channels that may cause unsuccessful reception of frames due to transmission errors can be embedded in our analysis following the approach presented in [10].

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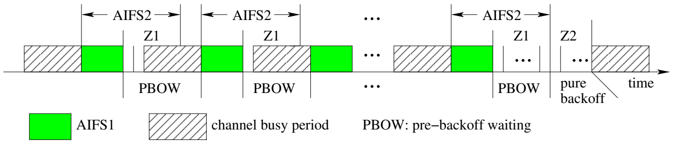

Fig. 2. An illustration of the pre-backoff waiting periods for AC_2

Similarly, $E[B_i]$ can be obtained as

$$E[B_i] = \sum_{j=0}^{m-1} (P_i^j b_j), \quad i = 1, 2, \tag{3}$$

where $b_j = CW_j/2$ is the average number of backoff slots in backoff stage j, $j = 0, \dots, m$, and m is the retry limit. Note that the class-dependent CW parameters have been included in the analysis.

According to the protocol, an AC_2 station can transmit only in Zone 2, as shown in Fig. 1. In this zone, both classes of stations can contend for channel access. A frame transmitted by the tagged AC_2 station will experience a collision when any one or more of the other stations from any class transmit in the same slot. Therefore, the collision probability for a frame transmitted by the tagged AC_2 station is given by

$$P_2 = 1 - (1-\tau_1)^{N_1}(1-\tau_2)^{N_2-1}. \tag{4}$$

For the tagged AC_1 station, its transmission can occur in either Zone 1 or Zone 2, in which the contention situations are different. In Zone 1, only AC_1 stations contend for channel access, while in Zone 2 stations from both classes contend. Therefore, the collision probabilities in Zones 1 and 2 are given by

$$P_{1,1} = 1 - (1-\tau_1)^{N_1-1}, \tag{5}$$
$$P_{1,2} = 1 - (1-\tau_1)^{N_1-1}(1-\tau_2)^{N_2}. \tag{6}$$

To obtain the average collision probability P_1, we also need the probabilities θ_i $(i = 1, 2)$ of a frame transmitted by the tagged AC_1 station in Zone 1 or 2, respectively. Let M denote the number of slots in Zone 1. For a frame transmission from the tagged AC_1 station, it occurs in Zone 2 only when neither itself nor any of the other AC_1 stations transmits in the M consecutive slots in Zone 1. Therefore, we have

$$\theta_2 = \big((1-\tau_1)^{N_1}\big)^M, \tag{7}$$
$$\theta_1 = 1 - \theta_2. \tag{8}$$

Thus, the average collision probability of an AC_1 station is

$$P_1 = \theta_1 P_{1,1} + \theta_2 P_{1,2}. \tag{9}$$

So far, we have obtained equations (1), (4) and (9) for the four variables $(\tau_1, \tau_2, P_1, P_2)$, which can be solved jointly by numerical method.

2) Average Frame Service Time: For the tagged AC_1 station, it spends $E[Z] = E[R_1] + E[B_1]$ generic slots to transmit a frame successfully, on average. Among the $E[Z]$ generic slots, $E[Z]\theta_1$ are in Zone 1 and $E[Z]\theta_2$ are in Zone 2. The average length of a generic slot in Zone i $(i = 1, 2)$ can be computed as

$$E[S_i] = a_i\Delta + b_i \cdot T_s + c_i \cdot T_c, \tag{10}$$

where $T_s = AIFS_1 + T_{data} + SIFS + T_{ACK}$ and $T_c \approx T_s$; a_i, b_i and c_i are the probabilities of the channel being idle, containing a successful transmission or a collision in Zone i, respectively. It is not difficult to obtain these probabilities as

$$\begin{aligned} a_1 &= (1-\tau_1)^{N_1}, & a_2 &= (1-\tau_1)^{N_1}(1-\tau_2)^{N_2}, \\ b_1 &= N_1\tau_1(1-\tau_1)^{N_1-1}, & b_2 &= N_1\tau_1(1-\tau_1)^{N_1-1}(1-\tau_2)^{N_2} \\ & & &\quad + N_2\tau_2(1-\tau_2)^{N_2-1}(1-\tau_1)^{N_1}, \end{aligned}$$

and $c_i = (1 - a_i - b_i)$, $i = 1, 2$. Then, the average frame service time for AC_1 is given by

$$\zeta_1 = \big(E[R_1] + E[B_1]\big)\big(\theta_1 E[S_1] + \theta_2 E[S_2]\big) \tag{11}$$

The frame service time of the tagged AC_2 station is composed of two parts. One is similar to the AC_1 case, which is the time an AC_2 station spends in Zone 2, and is given by

$$\xi = \big(E[R_2] + E[B_2]\big)E[S_2]. \tag{12}$$

The other can be derived as follows. As shown in Fig. 2, when the tagged AC_2 station is backing off in Zone 2, the backoff procedure is interrupted when any station transmits, which occurs with probability $1 - a_2$. Therefore, the backoff procedure of total $E[B_2]$ slots is divided into $E[B_2](1 - a_2)$ segments. In each segment, only when there are M consecutive idle slots (i.e., an idle Zone 1) after the end of a channel busy period can the AC_2 stations start their backoff counter decrementing procedure. This occurs with probability equal to θ_2. With probability θ_1, one or more AC_1 stations may transmit in any of the slot in Zone 1 and the current uncompleted Zone 1 is ended immediately by this transmission. Therefore, for each backoff segment of the tagged AC_2 station, there are $1/\theta_2$ such so-called "pre-backoff waiting" periods preceding the "pure" backoff stage. The mean length of the pre-backoff waiting periods is given by [12]

$$\overline{W} = \frac{(1-a_1)\sum_{i=1}^{M} a_1^{i-1}\big((i-1)\Delta + Ts\big)}{1-a_1^M}. \tag{13}$$

Thus, the total time spent in such pre-backoff waiting periods by the tagged AC_2 station is given by

$$\omega = E[B_2](1-a_2)\frac{\overline{W}}{\theta_2}. \tag{14}$$

Summing up the two parts given in (12) and (14), we obtain the average frame service time for the tagged AC_2 station as

$$\zeta_2 = \xi + \omega. \tag{15}$$

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Since there is only one successful transmission in $\zeta_i, i = 1, 2$, the per station normalized throughput of AC_i is

$$\eta_i = \frac{E[P]}{\zeta_i}, \tag{16}$$

where $E[P]$ is the average payload transmission time. In addition, the network normalized throughput is given by

$$\eta = N_1\eta_1 + N_2\eta_2. \tag{17}$$

C. The Analysis for Unsaturated Stations

The key difference between an unsaturated and a saturated station is that the former only contends for channel access when it has a frame to be serviced, which occurs whenever the MAC buffer is non-empty. For a loss-less queueing system[2], the probability of non-empty buffer is given by the server utilization factor $\rho = \zeta\lambda$, where λ is the average frame arrival rate and ζ is the average frame service time. In other words, an unsaturated AC_i station transmits in a randomly chosen generic slot with probability $\tau_i\rho_i, \rho_i \in (0, 1],\ i = 1, 2$. In the following, the symbols with the superscript $'$ represent unsaturated parameters.

We start with the tagged AC_2 station. Directly from the above argument, we obtain the collision probability of its frame as

$$P_2 = 1 - (1 - \tau_1'\rho_1)^{N_1}(1 - \tau_2'\rho_2)^{N_2-1}. \tag{18}$$

For the tagged AC_1 station, the collision probabilities in Zones 1 and 2 are

$$P_{1,1}' = 1 - (1 - \tau_1'\rho_1)^{N_1-1}, \tag{19}$$

$$P_{1,2}' = 1 - (1 - \tau_1'\rho_1)^{N_1-1}(1 - \tau_2'\rho_2)^{N_2}, . \tag{20}$$

and the probability of transmitting in Zone 2 is

$$\theta_2' = \left((1 - \tau_1'\rho_1)^{N_1-1}(1 - \tau_1')\right)^M, \tag{21}$$

because the tagged AC_1 station is contending with probability τ_1' while others are with $\tau_1'\rho_1$ only. Moreover, $\theta_1' = 1 - \theta_2'$, and the average collision probability of an AC_1 station is

$$P_1' = \theta_1' P_{1,1}' + \theta_2' P_{1,2}'. \tag{22}$$

The transmitting probabilities τ_i' $(i = 1, 2)$ remain as the same functions of the corresponding P_i' as shown in (1).

TABLE I
PARAMETERS USED IN THE PERFORMANCE EVALUATION

Channel rate	110 Mbps	Retry limit	7
Slot time	9 μs	Max. backoff stage	6
SIFS	10 μs	Min. contention window	32
PHY header	13.125 μs	Frame payload	500 bytes

The unknowns ρ_1 and ρ_2 in the above equations can only be determined with ζ_1' and ζ_2', the average frame service time for the unsaturated AC_1 and AC_2 stations, respectively. The latter two items can be obtained following the procedure given in Section III-B2. However, the key parameters of having an idle channel, successful transmission or collision in a slot of Zones 1 and 2 are changed to

$$\begin{aligned}
a_1' &= (1 - \tau_1\rho_1)^{N_1}, \qquad b_1' = N_1\tau_1\rho_1(1 - \tau_1\rho_1)^{N_1-1},\\
a_2' &= (1 - \tau_1\rho_1)^{N_1}(1 - \tau_2\rho_2)^{N_2},\\
b_2' &= N_1\tau_1\rho_1(1 - \tau_1\rho_2)^{N_1-1}(1 - \tau_2\rho_2)^{N_2}\\
&\quad + N_2\tau_2\rho_2(1 - \tau_2\rho_2)^{N_2-1}(1 - \tau_1\rho_1)^{N_1},
\end{aligned}$$

and $c_i' = (1 - a_i' - b_i')$, $i = 1, 2$. With these key parameters, we can proceed to obtain the unsaturated versions of equations (10)-(15), which can be combined together with (18)-(22), the unsaturated version of (1) and $\rho_i = \zeta_i'\lambda_i$ $(i = 1, 2)$ to give $(\tau_1', \tau_2', P_1', P_2', \rho_1, \rho_2)$, and more importantly, the desired average frame service times ζ_1' and ζ_2'.

Note that for a network with unsaturated stations, the per station throughput η_i' equals the incoming traffic load to the station. That is, the relationship between normalized throughput and service time shown in (16) does *not* hold for unsaturated stations. This is the main obstacle in extending those previously reported models to the unsaturated station case.

IV. NUMERICAL RESULTS

To demonstrate the analytical accuracy of the proposed model, extensive simulations have been run using our event-driven simulator. All the numerical results reported here are obtained based on the PHY and MAC parameters listed in Table I. There are $2N$ $(N = N_1 = N_2)$ peer-to-peer flows in the one-hop network, where half of the flows carry AC_1 traffic, and the remaining half with AC_2 traffic, all using the basic access mode. Due to space limit, in what follows we fix the minimum contention window size and TXOP for all ACs and only report the results relevant to the impact of $AIFS$.

We first consider the saturation case, where each station is backlogged with constant bit rate traffic. In Fig. 3 we show the average frame service time ratio (ζ_2/ζ_1) under different M. The agreement between the analysis results and the simulation ones suggests that our model is fairly accurate. It can be seen that, the delay ratio increases as M increases. This is because a larger M implies a longer graceful period that the high-priority AC could observe and in turn longer *pre-backoff waiting periods* the low-priority AC may incur. The increasing trend is more prevalent for larger number of stations. Fig. 4 shows the per station throughput for $N_1 = N_2 = 10$, which indicates the low-priority AC_2 is particularly sensitive to the increase of M than the high-priority AC_1's. As M changes from 1 to 6, the throughput loss of AC_2 is about 88%, and the throughput increase of AC_1 is about 54%.

For the unsaturated case, the average service time versus the frame arrival rate is shown in Fig. 5. Here we set 5

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[2] In practice, the MAC buffer usually can accommodate tens of frames, which is in effect very close to a loss-less system. Also, ρ is upper bounded by one, upon which the station becomes saturated and the analysis in this subsection reduce to the one in Section III-B.

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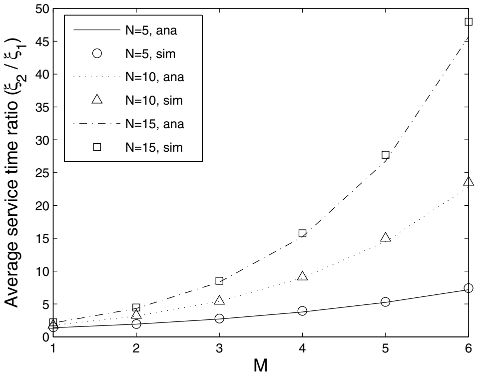

Fig. 3. Average frame service time ratio ζ_2/ζ_1 $vs.$ M for saturated stations.

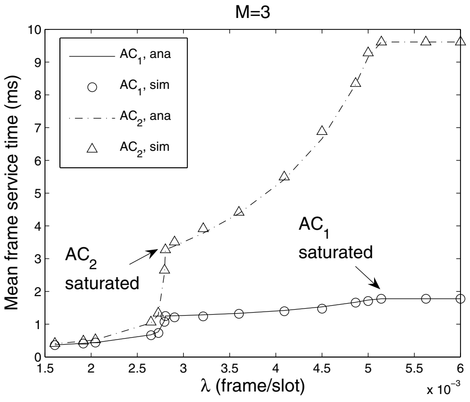

Fig. 5. Average frame service time $vs.$ frame arrival rate.

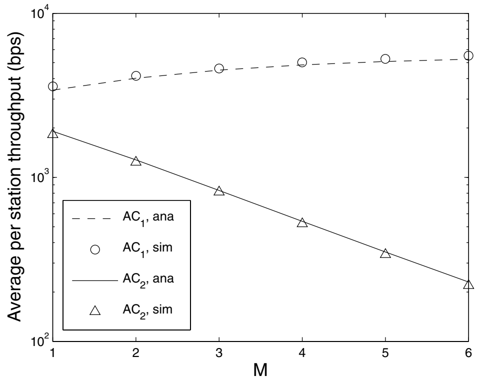

Fig. 4. Per station throughput for saturated stations.

flows for each AC. The analytical results match the simulation results very well. For mild traffic load ($\lambda < 2.8 \times 10^{-3}$), both ACs are unsaturated, but AC_2 is much more sensitive to the traffic volume increase than AC_1. At certain point ($\lambda \approx 2.8 \times 10^{-3}$) the low-priority AC_2 becomes saturated and its queue accumulates rapidly. If we keep increasing the traffic arrival rate, the AC_1 stations will incur longer frame service time, but the increase rate is lower than the case when both AC_1 and AC_2 are unsaturated. Eventually both ACs become saturated and behave the same as the saturation case discussed previously. From this figure, we can see that the impact of $AIFS$ in unsaturated condition is different from that in saturated condition. This reveals the significance of our model, as most conventional models are unmanageable to analyze unsaturated case.

V. CONCLUSION

We have presented a novel analytical model for the distributed prioritized channel access mechanisms adopted by EDCA for WLANs and PCA for WPANs. Compared with existing models that are only for the saturation case, the proposed model is applicable to both saturated and unsaturated stations because it is developed based on the fundamental relationship between the average frame service time and the per station throughput. It is this favorable feature that enables us to reveal the different effects of the same mechanisms in different situations, which, to our knowledge, is reported for the first time in the open literature. Due to space limit, we only present the analysis of a network with two access classes and the effects of AIFS. The analysis of more access classes and other mechanisms can be found in [12].

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